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NO-GIMBAL FEASIBILITY FLIGHT TEST PROGRAM

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AERONAUTICAL SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 5201, Task No. 520104

(Prepared under Contract No. AF 33(616)-8463 by:
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NOTICES

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FOREWORD

This report was prepared by Ford Instrument Company, Long Island City 1, New York, in accordance with Air Force Contract AF 33(616)-8463, under Task No. 520104 of Project No. 5201, entitled No-Gimbal Feasibility Flight Test.

The flight test program described herein represents the third and concluding phase of an overall program whose objectives were the feasibility study, development, fabrication, and flight testing of a breadboard model of a Pure Integral No-Gimbal System using strap-down inertial components. Phase 1, the feasibility study, Contract AF 33(616)-5858, was concerned with the theoretical determination of feasibility and the optimization of the No-Gimbal System design parameters. This study was completed in May 1959. The conclusions and recommendations of the study program were reported in a Summary Engineering Report submitted to WADD in June 1959. The major conclusion of the study was that the strap-down or no-gimbal concept for inertial navigation was theoretically feasible, and that it was possible to design a system of this type with accuracies comparable to those of gimballed pure integral inertial systems with state-of-the-art sensors. As a result of this work, Ford Instrument Company was awarded Contract AF 33(616)-6734 to design and fabricate a breadboard model of the system. This effort was completed in September 1961, and is described in Technical Documentary Report ASD TR 61-484.

Immediately upon conclusion of the fabrication effort, work began on the flight test evaluation. This work was concluded in August 1962. The work was administered under the direction of the Navigation and Guidance Laboratory. Mr. A.R. Turley was project engineer for the Laboratory.

The following members of Ford Instrument Company's engineering staff assisted in the preparation of this report, and their contributions are gratefully acknowledged:

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This report concludes the work of Contract AF 33(616)-8463.

ABSTRACT

This Technical Documentary Report describes the flight test evaluation of the Pure Integral No-Gimbal System under Air Force Contract 33 (616)-8463. The program successfully demonstrated the feasibility of a strap-down inertial navigation system and verified the predicted performance of the breadboard model of the system.

The report describes the results of eight flight and two ground tests during which approximately 40 hours of system operation, including 20 hours in the air and 20 hours on the ground, were accumulated. A complete description of the flight test and data processing procedure is presented herein as well as a description of special equipment designed for the evaluation program. A brief summary of system operation is also included. Finally, recommendations for follow-up programs, which would investigate improvements in, and certain applications for a No-Gimbal System, are presented.

PUBLICATION REVIEW

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I. INTRODUCTION

Contract AF 33(616)-8463 provided for the evaluation of a breadboard model of the Pure Integral No-Gimbal System by means of flight testing. The objectives of the program were to demonstrate the feasibility of an inertial navigation system using strap-down sensors and to determine the performance of the system under operational conditions. Both objectives were to be accomplished by comparing the accuracy of the system as determined by flight testing with that predicted by analysis during the feasibility study, Contract AF 33(616)-5858.

The procedure utilized during the performance of flight tests consisted of flying the inertial sensor package and the altimeter, and recording the outputs of these sensors on magnetic tape. Periodic photographs of the ground were taken during flight to provide position fixes with which to compare the corresponding system determined values. Subsequent to each flight, the recorded data was processed on a ground-based general-purpose computer programmed to perform the required no-gimbal computation. The solutions to these computations were periodic indications of vehicle latitude and longitude during each flight. Comparison of the computed position coordinates with the photographically determined position references provided the data necessary for establishing system accuracy.

Flight tests were performed at the Sperry Flight Research Facility at MacArthur Field, Long Island, New York, in a Sperry Rand DC-3 aircraft. Processing of the recorded flight data was accomplished at the ASD Computer Facility in Dayton, Ohio. Subsequent to each flight, the magnetic tape containing the flight data was transported from New York to Dayton via commercial airliner. After processing, the results of each flight

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were transmitted back to the Ford Instrument Company plant in New York where the results were analyzed. Flight tests were performed only after the data of the preceding flight were reduced. If the results were unsatisfactory, the cause was determined and corrected before another flight test was attempted.

Approximately 40 hours of test data were accumulated during the flight test phase of the program. This time consisted of 20 hours of actual flight time and 13 hours of ground time prior to and after each flight. In addition to the flight tests, two ground tests having a total duration of 7 hours were performed. The flights were flown in various directions and at various altitudes in the New York, New Jersey, Pennsylvania, and New England area. A program of exaggerated maneuvers was carried out during one of the flights. Although the performance of the flight test program was in general agreement with original plans, a number of equipment difficulties was encountered during the program. These difficulties are discussed later in this report. However, in all cases, the difficulties were the result of equipment failure, and did not affect the planned program or the final conclusions.

Details of the flight test results as well as a detailed description of the system and of the flight test equipment and procedures appear in subsequent sections of this report.

II. FLIGHT TEST RESULTS

A. Summary of Test Program

This section describes in detail the results of the flight test program and presents accuracy data for each of the successful flights. A summary of the test program is shown in the chart of Figure 1. This chart indicates the duration of each flight or ground test as well as indicating significant events, e.g., takeoff, landing, etc., during each test. As shown in the chart, eight flights were flown. (This does not include one equipment shakedown flight made prior to the main series.) The flight tests were generally of 4 hours duration and included north-south and east-west flights as well as flights at other than cardinal headings. The flights were made at various altitudes up to 10,000 feet and at air speeds of approximately 130 mph.

Before each flight, the sensor package was aligned in a local level, north-south orientation to provide knowledge of initial conditions for the attitude computation. Prior to the conclusion of a number of flights (those marked with a circle), the sensor package was physically realigned to its initial orientation to permit a check of the accuracy of the attitude computation (the final values of the direction cosines defining sensor package attitude should agree with the initial values when due allowance is made for earth rotation during the test period). During flight No. 8, a program of maneuvers was executed to determine the ability of the system to operate in the presence of high rotational rates. Rotational rates of up to 7 degrees per second were registered during this period. (The breadboard system is designed to operate at rotational rates of up to 1 radian per second, which might consist of rotational vibration in addition to gross vehicle motion.)

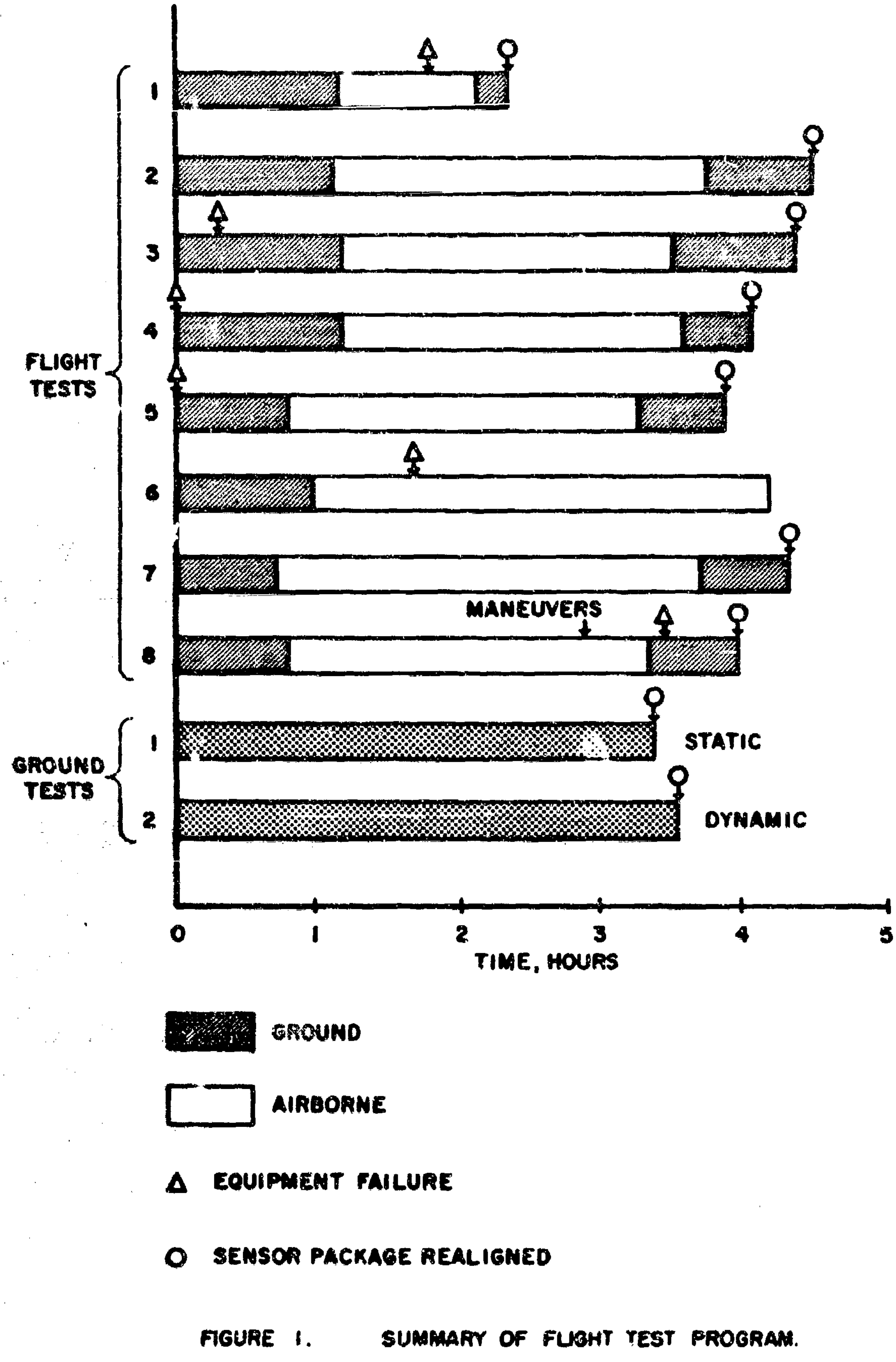


FIGURE 1. SUMMARY OF FLIGHT TEST PROGRAM.

In addition to the flight tests, two ground tests were performed. The first was a static test during which the sensor package was maintained stationary so that the only inputs sensed were the rotational rate due to earth's motion and the apparent acceleration due to gravity. This test was performed to determine a "standard" that might enable the separation of any unique effects caused by vehicle motion from errors in a stationary system.

The second ground test was a dynamic test during which rotational rates greater than those experienced in the aircraft and approaching the design limits of the sensor package were applied. This was performed as a further test of the system with high input rates.

Equipment failures are indicated in the chart of Figure 1 at the time of their occurrence by the delta symbol. A description of each malfunction is given in Table 1. In addition to the equipment malfunctions encountered during flight tests, a number of problems arose during the debugging and preflight test periods. These difficulties were primarily with the operation of the tape recorder and the compressor of the accelerometer air supply. Because of the latter difficulty and in order not to delay the program, two flights were made with bottled nitrogen gas substituted for the regenerative air supply. However, the inertial sensor package operated reliably throughout the entire program, despite the many hours logged on the sensors during the present program and the previous fabrication contract. Significantly, the ratio of successful flight and ground data time to total time was about 60 percent, a ratio that is believed to be rather high for an evaluation program of this type.

Table 1. Equipment Malfunctions during Flight Tests

Flight Test No.	Equipment Malfunction
1	Partial erasure of recorded data on one accelerometer channel during rewinding of tape caused by faulty write amplifier in tape recorder.
3	Loss of synchronism in transferring recorded data into computer caused by large variation in spacing of timing marks. Resulted from excessive tape recorder flutter or speed variation.
4	Loss of information on one gyro recording channel caused by faulty connector pin on synchronizer and parity generator unit.
5	Loss of recorded information caused by an intermittent write permit signal on tape recorder.
6 and 8	Apparent intermittent connection in wiring between sensor package and the synchronizer and parity generator.

Besides equipment problems, delays were encountered due to aircraft scheduling difficulties (which were compounded when the aircraft was removed from service for a two-week period for relicensing tests, and when these tests revealed that an engine had to be replaced requiring another two-week delay). Problems were also encountered during the debugging of the system comprising the magnetic tape reader, buffer unit, and computer, largely because this process utilized a special input channel of the converter, which was installed especially for this program and which was being used for the first time with the computer. The complex scheduling problem, which involved reserving time on the aircraft and on the computer and arranging for transmission of data to and from the computer facility before the next flight could be flown, also resulted in some delays. Because both the aircraft and the computer had to be scheduled at least one week in advance, any delay in the flight or in processing or analyzing data was compounded by requiring the alteration of other planned schedules. Fortunately, weather was not a serious factor; only once did bad weather cause cancellation of a scheduled flight.

B. Test Results

The flight test results are summarized in Table 2. This table lists east-west, north-south, and radial errors and error rates for each test during which a significant amount of test time was logged. The errors listed are those at the end of each test period. The root mean square values of the error rates are also listed.

The root mean square error rate for all successful flights was 4.3 miles per hour. This figure is significantly better than the predicted accuracy of 10 miles per hour. The predicted figure is based upon the fact that the most significant error is that due to gyro drift, all other system errors being small in comparison, and

Table 2. Summary of System Performance

Flight Test No.	Ground Test No.	Time (hrs)	East-West Error (miles)	East-West Error Rate (mph)	North-South Error (miles)	North-South Error Rate (mph)	Radial Error (miles)	Radial Error Rate (mph)
1		1.8	1.5	0.8	4.4	2.4	4.6	2.6
2		4.6	9.6	2.1	4.8	1.0	10.8	2.3
6		1.7	6.4	3.8	8.0	4.7	10.3	6.0
7		4.4	4.5	1.0	28.0	6.4	28.5	6.5
8		3.6	13.8	3.9	6.5	1.8	15.4	4.3
	1	3.5	1.9	0.5	7.0	2.0	7.2	2.1
	2	3.6	8.5	2.4	8.0	2.2	11.6	3.2
RMS Error Rate (mph)				2.3		3.4		4.2

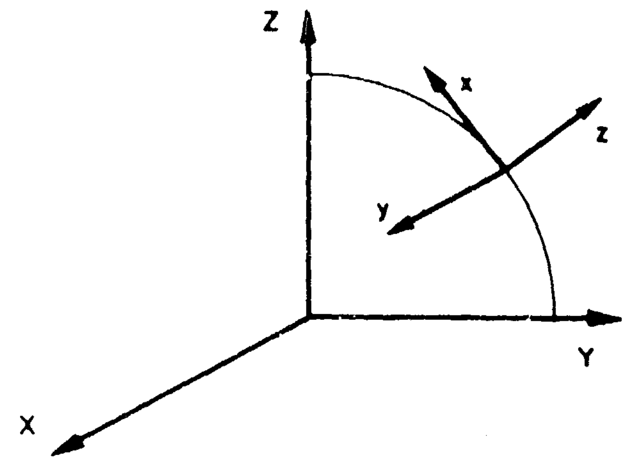
upon a predicted drift rate of 0.1 degree per hour (assumed constant in the analysis). Further experience with the gyros indicated that, with the drift compensation technique that was being applied, drift rates of the order of one-half this value were attained. Still, the experimental error compares very favorably with the predicted value and confirms the theoretical analysis of system performance.

No precise correlation between total system error and the error introduced by a specific cause can be made. However, it is possible to examine the accuracy with which the attitude of the sensor package was determined, thereby obtaining some idea of the performance of that portion of the system.

This information is available for the four tests in which no equipment malfunctions occurred and in which the sensor package was realigned prior to concluding the run. When the amount of earth's rotation during the test is compensated for, the direction cosines at the conclusion of the test should agree exactly with the corresponding initial values. Discrepancies would be due to gyro drift and any errors in the attitude computation. The results of these tests are indicated in Figure 2, which lists the error, converted to minutes of arc, in each of the nine direction cosines at the end of the test period. The maximum error in any cosine was in the order of 15 minutes for a 4-1/2 hour period. This corresponds to an error rate of approximately 0.05 degree per hour. Since this compares with the expected gyro drift rate, it may be concluded that gyro drift is the most significant source of error in the determination of attitude, and that computational errors are small in comparison. Furthermore, since the above error rate in attitude could alone account for the observed position errors, it may also be concluded that any errors introduced by the remainder of the system are negligible.

The results of each of the successful tests are presented in the curves of Figures 3 to 9. In each of the figures, east-west and north-south as well as radial errors are plotted as a function of time. The system accuracy illustrated by this data is, as previously indicated, well within the specified performance criteria.

Another indication of system performance is the degree of orthonormality maintained by the direction cosine matrix relating coordinates in the body axis frame with those in the inertial reference frame. Any matrix (B) of direction cosines relating one orthogonal Cartesian coordinate frame to another must be orthonormal, i.e., the product of B with its transpose must yield a unit matrix. In a no-gimbal computation, it is possible for the direction cosine matrix to deviate from orthonormality after a



BODY SYSTEM: x, y, z

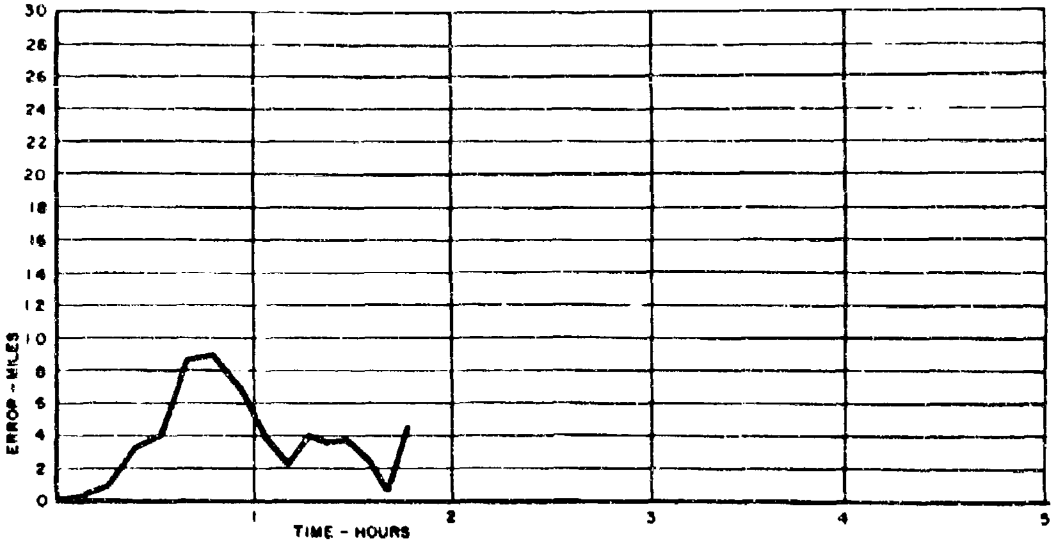
INERTIAL SYSTEM: X, Y, Z

(a) DEFINITION OF COORDINATE SYSTEMS

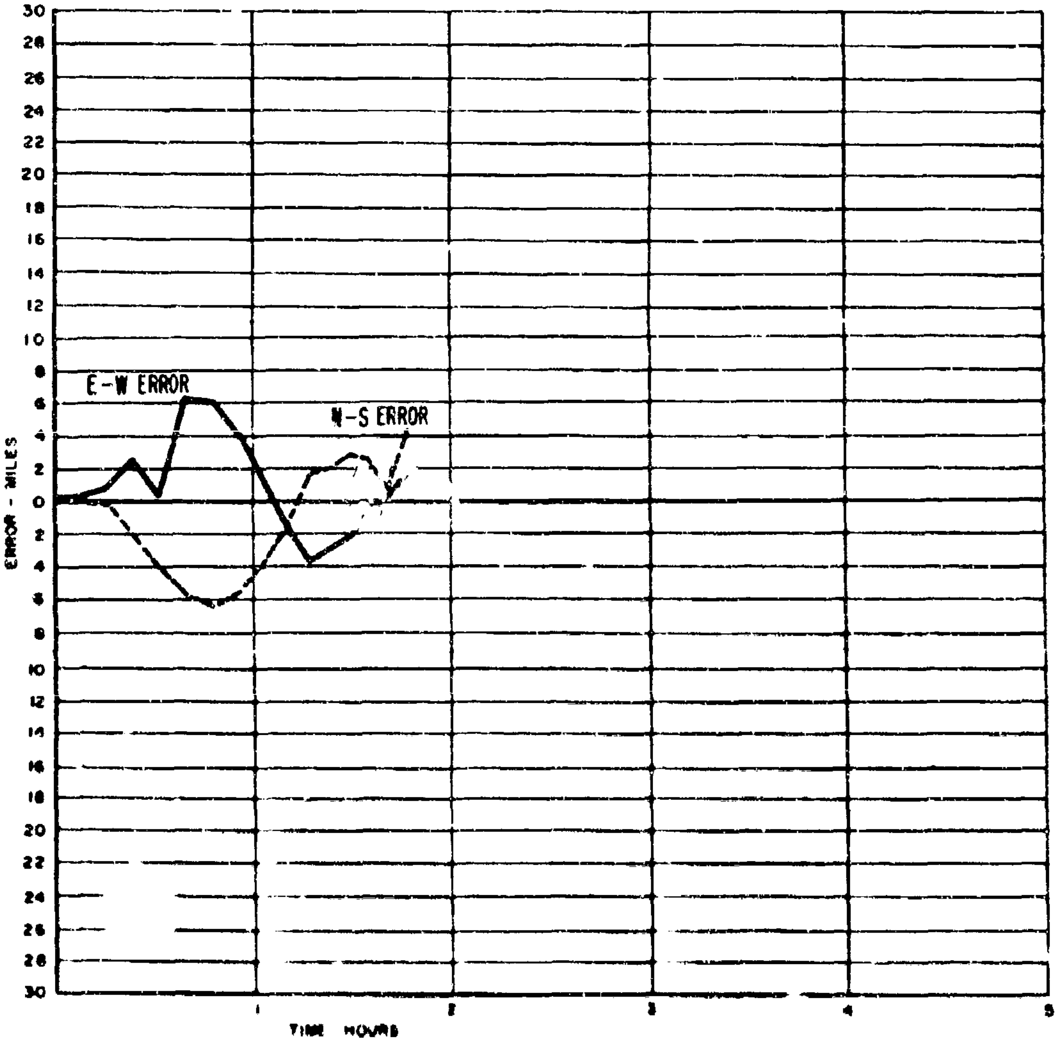
	FLIGHT NO. 2 4 HRS, 33 MIN			FLIGHT NO. 7 4 HRS, 27 MIN			GROUND TEST NO. 1 3 HRS, 27 MIN			GROUND TEST NO. 2 3 HRS, 35 MIN		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
x	0	7.4	7.4	0	15.4	15.4	11.2	-11.8	-11.8	-4.1	-6.8	-6.8
y	12.9	-11.7	-7.3	15.1	13.7	4.5	14.1	14.0	-2.7	7.9	4.9	9.5
z	-4.1	7.4	-7.4	-13.3	15.4	-15.4	-8.9	-11.8	11.8	-9.9	-6.8	6.8

(b) ERRORS IN DIRECTION COSINES -- MINUTES OF ARC

FIGURE 2. ERRORS IN COMPUTED DIRECTION COSINES FOR FLIGHT AND GROUND TESTS.

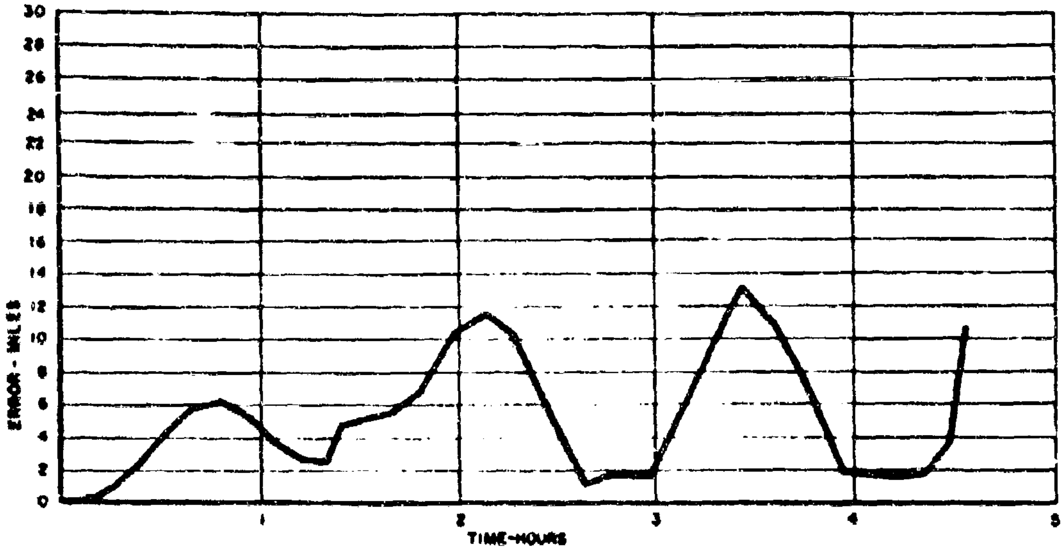


(a) RADIAL ERROR

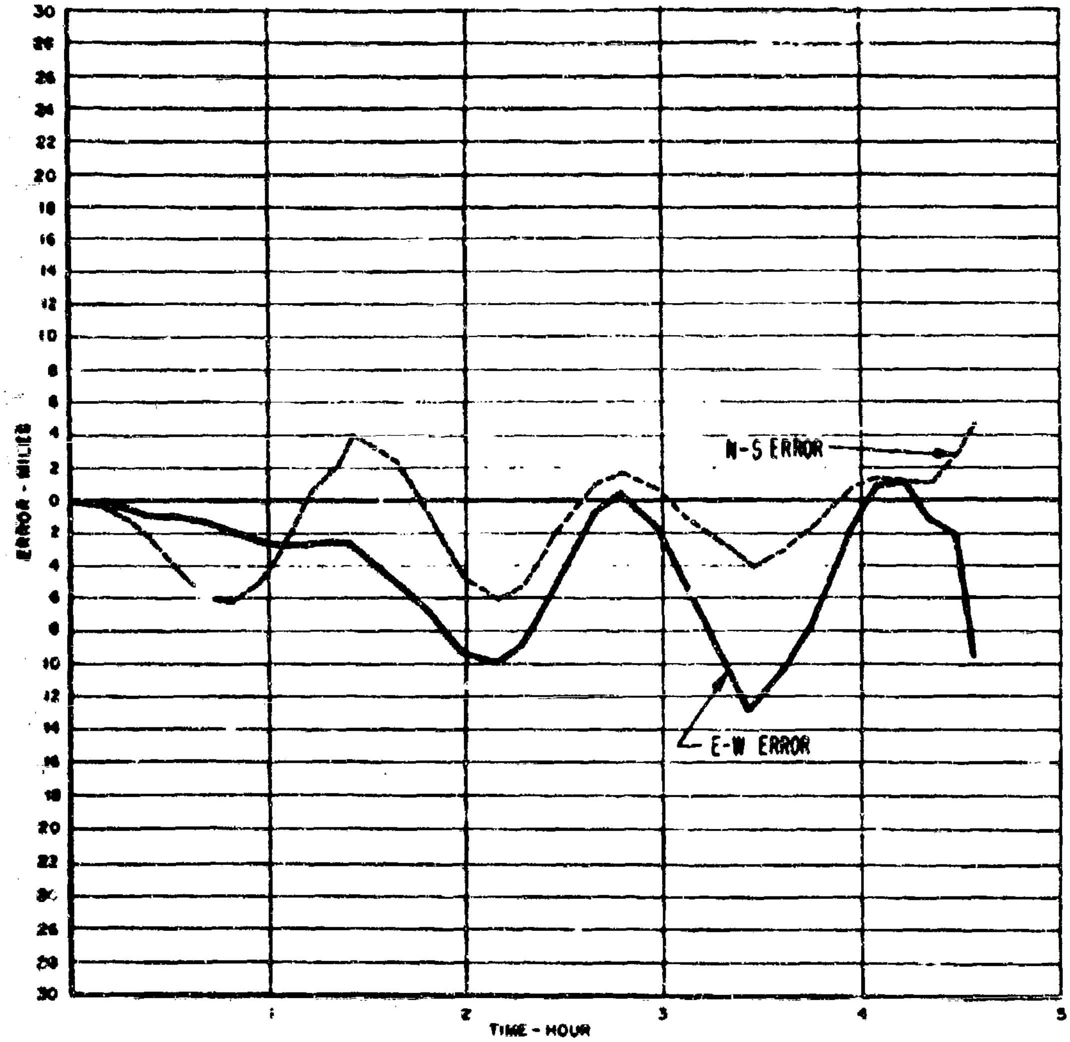


(b) E-W AND N S ERROR

FIGURE 3 POSITION ERROR VERSUS TIME - FLIGHT TEST NO. 1

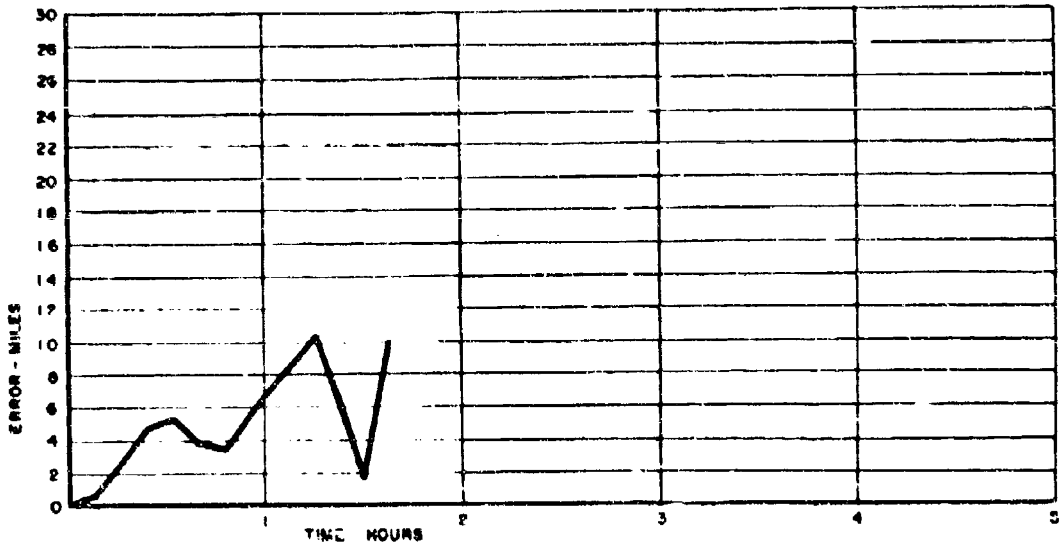


(a) RADIAL ERROR

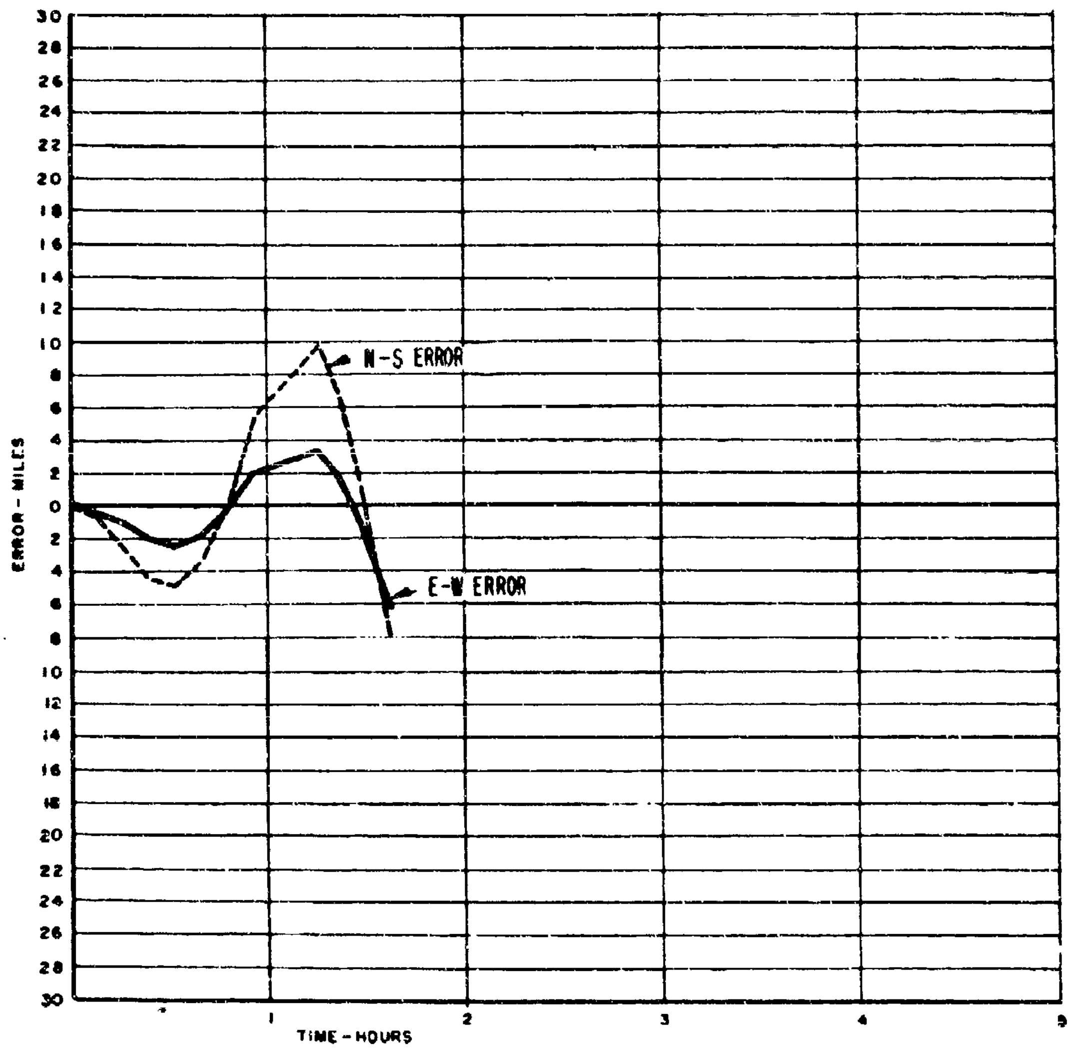


(b) E-W AND N-S ERROR

FIGURE 4. POSITION ERROR VERSUS TIME - FLIGHT TEST NO. 2



(a) RADIAL ERROR



(b) E-W AND N-S ERROR

FIGURE 5. POSITION ERROR VERSUS TIME - FLIGHT TEST NO. 6

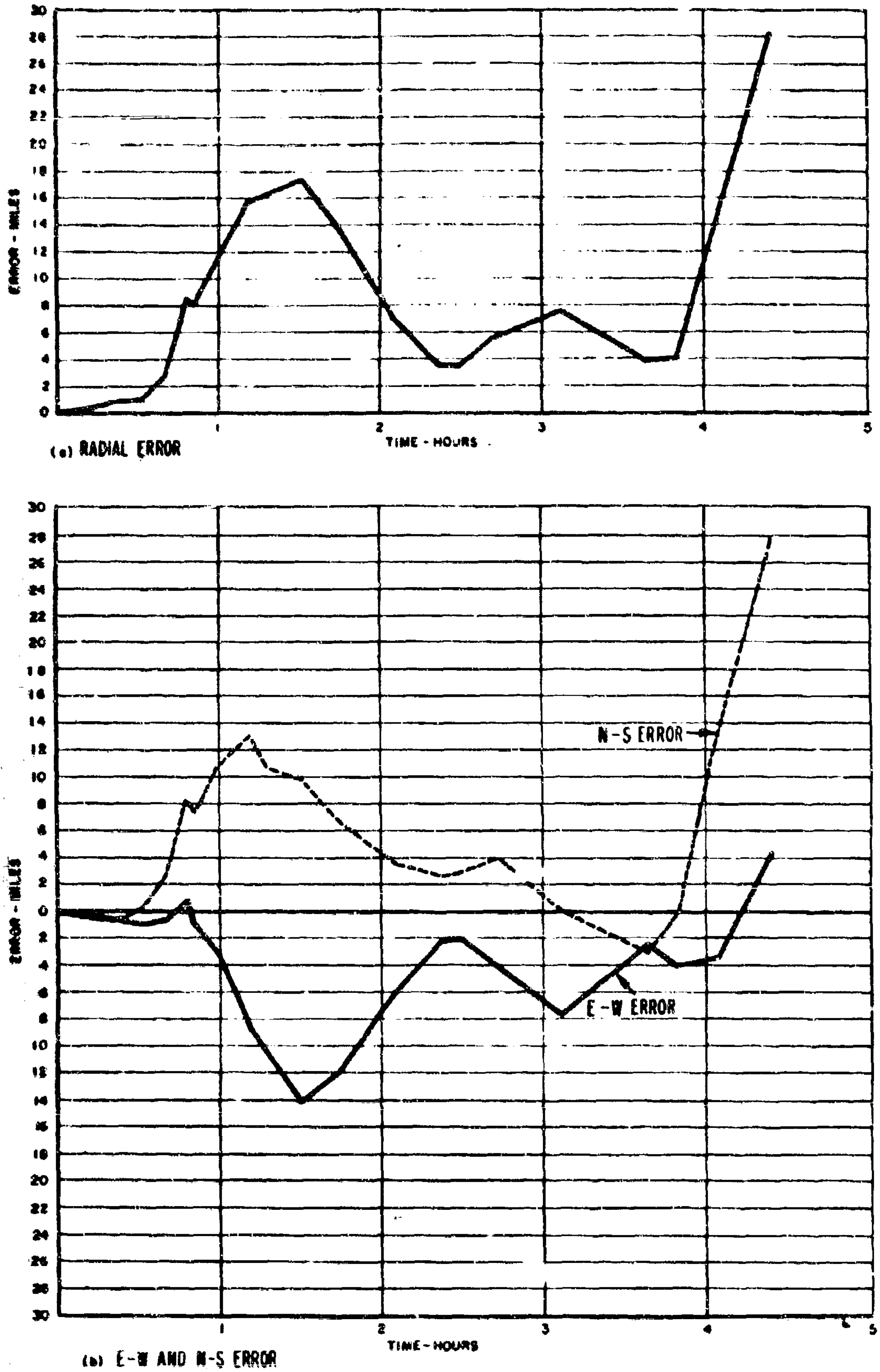


FIGURE 6. POSITION ERROR VERSUS TIME - FLIGHT TEST NO. 7

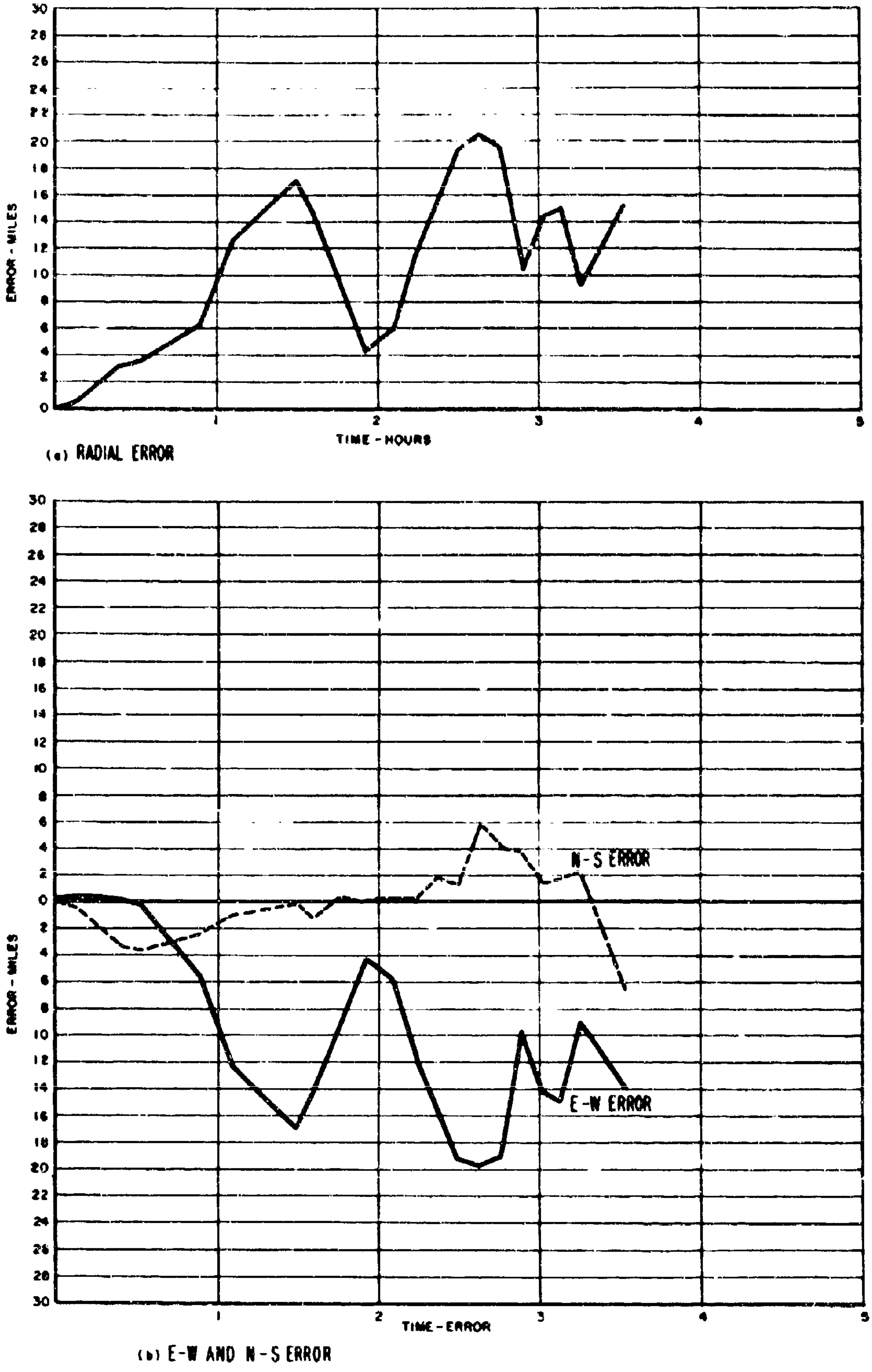


FIGURE 7. POSITION ERROR VERSUS TIME - FL'GHT TEST NO. 8

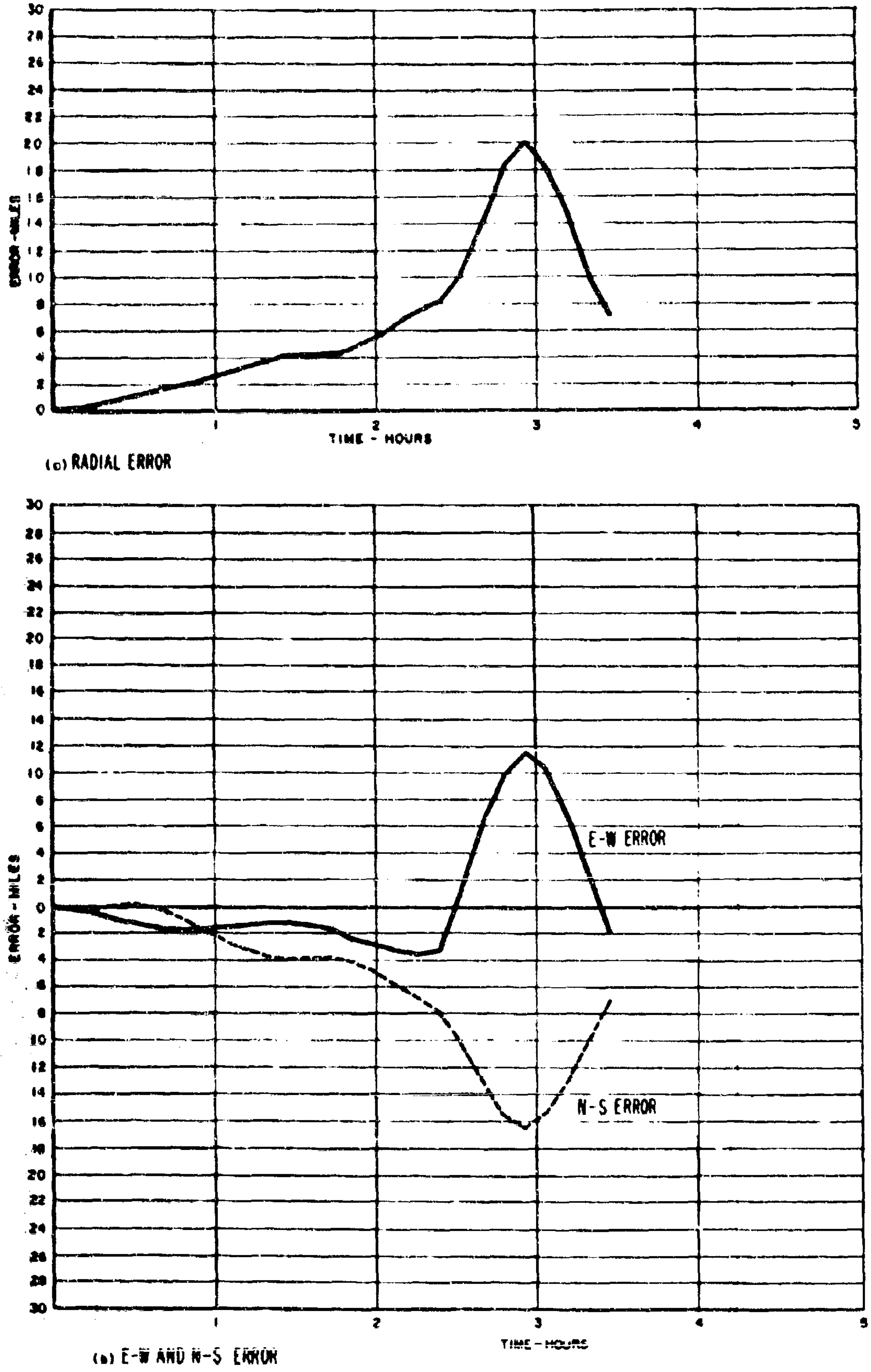
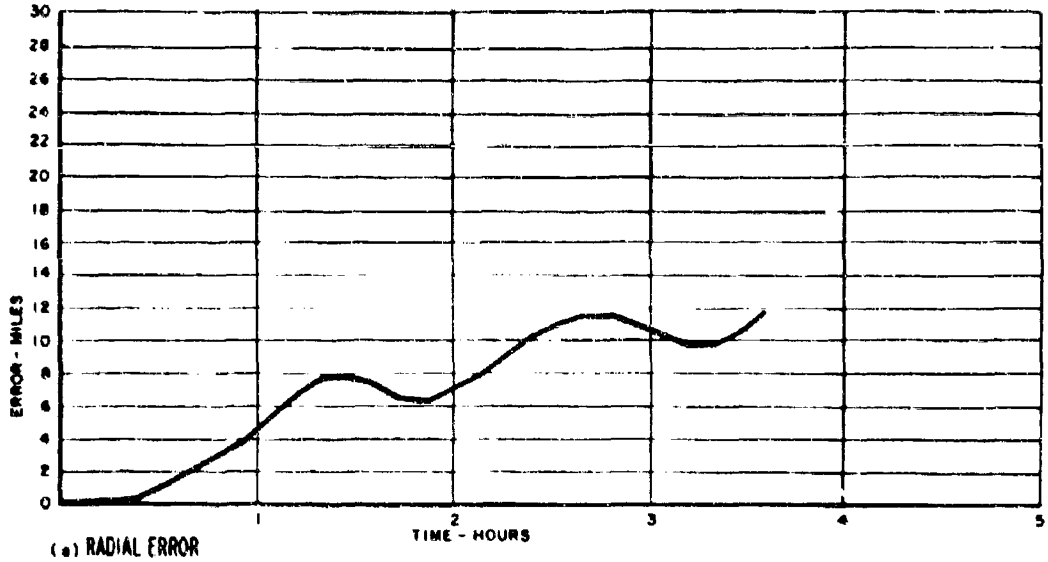
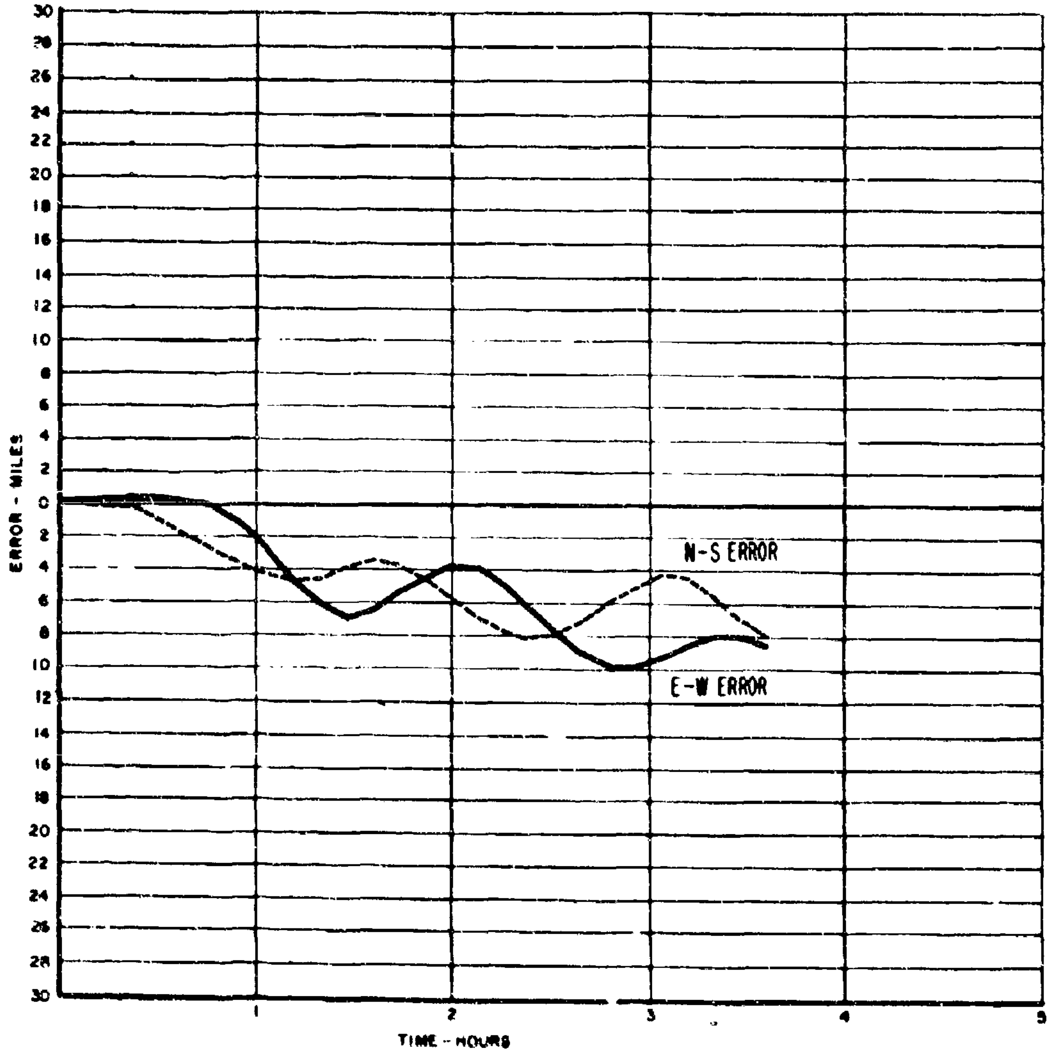


FIGURE 8. POSITION ERROR VERSUS TIME - GROUND TEST NO. 1



(a) RADIAL ERROR



(b) E-W AND N-S ERROR

FIGURE 9. POSITION ERROR VERSUS TIME - GROUND TEST NO. 2

large number of adjustments have been made on the matrix during the updating process. This is a result of truncation and roundoff error in this computation. During the study phase of this project, it was found that the second order algorithm for updating the B matrix reduced truncation error to a negligible level and that a 36-bit register was sufficiently long to obviate the possibility of excessive roundoff error. Consequently the deviation from orthonormality of the computed B matrix should be small. To substantiate this conclusion, the product of the B matrix and its transpose was periodically computed and examined during processing of the flight test data. The maximum deviation of any element of the product matrix from the corresponding element of the unit matrix at the end of flight was never greater than 3.7×10^{-5}. This deviation is extremely small and indicates that the effect of truncation and roundoff errors on the orthonormality of the matrix was negligible.

In conclusion, the amount of test data accumulated during the program, and the highly satisfactory performance indicated thereby, serve to verify predictions of system performance and to demonstrate the feasibility of the no-gimbal concept.

III. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Flight tests of the no-gimbal sensor package and subsequent processing of the data have provided conclusive evidence that a strap-down inertial system is feasible for vehicle navigation.

The performance specification for the breadboard model of the No-Gimbal System called for accuracies comparable to those of a conventional gimballed, pure integral inertial system when using comparable sensor components. This level of performance was achieved. All system errors could be accounted for by the gyro drift rates, which were measured prior to each flight and which would be expected in a platform configuration. There was no degradation of performance due to either the high angular rate and vibration environment imposed upon the sensors in a body-mounted system or to the errors involved in the high-speed incremental attitude computation peculiar to the strap-down system. Since, in most of the tests, the system error encountered was less than that attributable to expected gyro drift, it is entirely possible that the vibration to which the gyros were subjected and the continued change in orientation of the gyros due to vehicle motion may have affected the gyro drift in a beneficial manner. Several schemes that attempt to distribute errors due to gyro drift in a more random manner by purposeful controlled rotation of the gyro case have been suggested in recent literature. Since each gyro in a strap-down system naturally partakes of vehicle rotational motion, any advantages occurring from such motion would be obtained with no increased system complexity.

The major advantages that strap-down inertial systems promise to offer are indicated below.

1. Small size and weight: fully utilizes advances in digital computer art.

2. Versatile sensor configuration: readily custom-fitted to application, not restricted to spherical shape.

3. All-attitude operation: inherently free from gimbal-lock.

4. Rapid alignment: permits rapid leveling and aligning to match a reference inertial system (slewing is performed in the computer and no physical motion is required).

5. Compatible with supplementary system: ideal for use with body-mounted supplementary sensors such as doppler radar, celestial tracker, or odometer.

6. Exotic sensor utilization: computer compatible with contemplated exotic gyro output formats.

7. Mass production simplification: sensor package and computer ideal for "unitized" assembly.

8. Ease of maintanence: replacement of any component greatly simplified.

9. Freedom from obsolescence: advanced components readily "phased in."

Now that the feasibility of strap-down inertial navigation systems has been established, it is recommended that programs be immediately undertaken in several areas in order to derive maximum benefit from the inherent advantages of strap-down systems.

B. Recommendations for System Application

It is recommended that several study and design efforts be undertaken at this time. Two such efforts that would investigate certain specific applications of the strap-down concept are described below.

Operational aircraft navigation systems, presently in use, rarely rely upon pure inertial determination of position. Rather, these systems incorporate additional sensing equipment to bound the error caused by inertial sensor inaccuracies. It is common to employ additional information in the form of position fixes from celestial or map matching

devices, or in the form of velocity information from a doppler radar, to increase the accuracy of the position computation. In each of these cases, the specific configuration that would provide the optimum marriage between the strap-down inertial sensor package and the auxiliary sensor equipment remains to be established.

It is recommended that a study be undertaken to determine the optimum configuration in each case, thereby facilitating the eventual inclusion of a strap-down sensor package in an operational aircraft navigation system.

Another widespread use of inertial systems is in the guidance of ballistic missiles. Since there is a wide variety of guidance and control techniques in use today, and since the adaptation of the strap-down concept to each system requires a determination of the optimum computation scheme, it is recommended that a study be conducted to establish the optimum computation scheme in each case. This will facilitate the introduction of the strap-down concept to ballistic missile guidance. Ford Instrument Company has performed several in-house investigations on the application of the strap-down concept to an IRBM using correlated velocity guidance techniques. The results of these investigations indicate that a strap-down inertial guidance system for a ballistic missile is feasible within the present inertial sensor and digital computer state-of-the-art. The purpose of a design study would be twofold: (1) to investigate areas not covered in sufficient detail in the Company-sponsored activity; and (2) to use the results of these efforts to determine the preliminary design and predicted performance of an optimum strap-down inertial guidance

system for a mobile launched ballistic missile. The advantages of using an optimum strap-down inertial guidance system in conjunction with an algebraic-integration solution* for a mobile launched ballistic missile would be significant.

C. Recommendations for System Improvement

The combination of a body-mounted inertial sensor package with an attitude and coordinate conversion computer produces outputs of incremental velocity changes (including apparent velocity changes due to the gravitational field) relative to an inertial frame. Since this is identical with the output received from three integrating accelerometers mounted on a platform that is maintained stable in inertial space, the two systems may be considered equivalent. Consequently, any function that may be performed by such a stable platform, whether it be aircraft navigation, land navigation, ship or submarine navigation, missile guidance, or space probe navigation, may also be performed by a strapdown system. Strap-down inertial systems are then functionally competitive with stable platform inertial systems. However, it is necessary to establish the physical characteristics of a competitive strap-down system: i.e. to determine the size and weight that can be achieved with an operational strap-down inertial system. This topic is treated in the following paragraphs.

*Algebraic-integration solution refers to a unique navigation system that optimumly combines inertial information with that from an independent velocity measuring subsystem. The Algebraic-Integration System was developed by Ford Instrument Company for the Air Force under Contract AF 33(616)-5858. WADD-TR-60-923 completely describes the system.

Sensor Package. The body-mounted inertial sensor unit developed under Contract AF 33(616)-6734 and flight tested under this contract is a breadboard model. In constructing this model, size and weight considerations were subordinated to ease of fabrication and accessibility. Large size and weight penalties were incurred by the use of the large G2K2 gyros supplied as GFE for use in the rate integral gyros.

However, if a prototype inertial sensor package were to be constructed with sensors presently under development by Ford Instrument Company, the size of the package could be drastically reduced. It is estimated that this package would weigh approximately 20 pounds and occupy 325 cubic inches. It would be possible with a sensor package of this size to achieve attitude drift rates below 0.03 degree per hour, and to limit errors in the acceleration sensors to an almost negligible level. Ford Instrument Company is performing several in-house projects to develop these sensors, i.e., a miniature rate integral gyro and a miniature digital accelerometer. The concept of pulse torquing, which is being employed for the digital accelerometer, could possibly be applied to gyros in missile applications. This technique would further improve the size and weight of the system by replacing the rate integral gyro with a pulse torqued rate gyro, thereby eliminating the encoder and the hardware required to transform a rate gyro into a rate integral gyro.

Subsequent developments in the basic sensors of acceleration and attitude promise to improve the performance of body-mounted inertial package still further. It is expected that these new developments (electrostatic gyros, etc.) could be incorporated in a body-mounted inertial sensor package with relative ease.

Computer. An inertial system, based on the concept of body-mounted sensors, transfers the function of the relatively large and complex gimbal structure (required for stable platform systems) to a digital computer. The computer converts body frame sensor data to inertial frame data based on direction cosines, which are stored in the computer and regularly updated by it. In fact, as pointed out previously, the outputs from this combination (body-mounted sensors and attitude and coordinate conversion computers) are equivalent to those which would be obtained from three integrating accelerometers mounted on a platform stabilized relative to inertial space. Consequently, if body-oriented inertial systems are to compete with stable platform systems, the attitude computation and coordinate conversion must be achieved by a digital computer that is small and lightweight.

Ford Instrument Company recently performed an in-house effort to establish the preliminary logical design of such a computer, and to determine its expected size and weight based upon packaging techniques available to date.

By the use of present techniques, it is possible to build an attitude and coordinate conversion computer (designated as FORDAC III) with size and weight as shown in Figure 10. In 1 year, by using advanced techniques, it will be possible to further reduce the size and weight of the FORDAC computer to 135 cubic inches and 8 pounds.

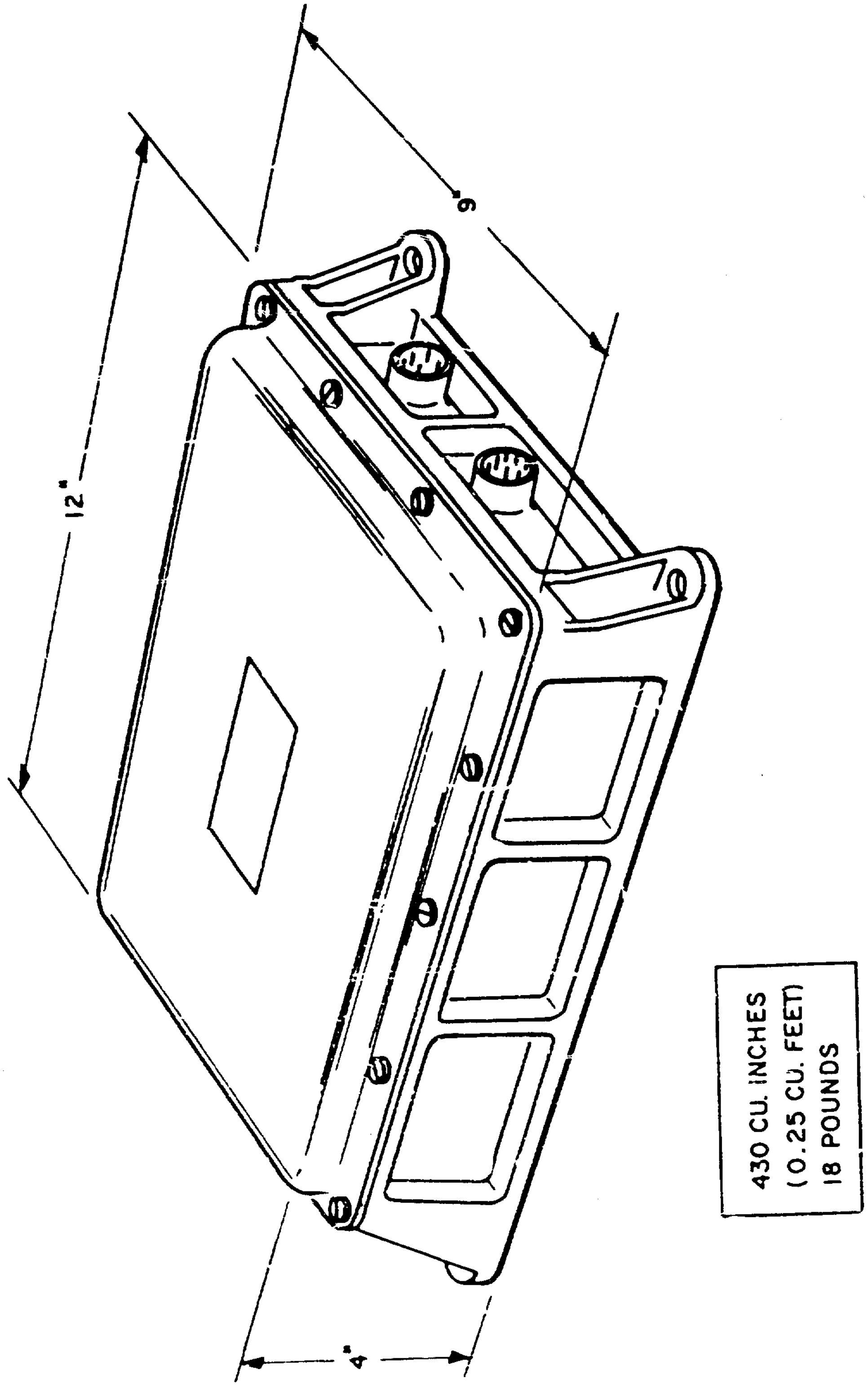


FIGURE 10. FORDAC III COORDINATE CONVERTER, OUTLINE DIMENSIONS.

IV. SYSTEM DESCRIPTION

A. Functional Operation

A functional block diagram of a self-contained Pure Integral No-Gimbal System is shown in Figure 11. Briefly, the system comprises seven passive sensors and a digital computer. Six of the seven sensors are inertial measuring devices, three strap-down rate integral gyros (see Appendix for description of operation) and three strap-down accelerometers, all mounted in a sensor package. The rate integral gyros sense the body axes components of the angular velocity and the accelerometers sense specific acceleration of the vehicle. The seventh sensor is an altimeter that is employed primarily for stabilization purposes. The computer consists of an attitude computation section and a position computation section.

In the attitude computation section, the nine direction cosines relating the body-axes conducted system to the axes of an earth-centered, inertially fixed, reference frame are continuously determined. These cosines are used to coordinate convert the accelerometer outputs by resolving them along the axes of the inertial frame. In the position computation section, a conventional position computation is then performed to determine the three Cartesian coordinates of position in the inertial frame. This information is then coordinate converted to provide latitude and longitude outputs, and to display this information in an appropriate manner.

For purposes of expediting the flight test program and achieving an earlier demonstration of system feasibility, not all of the above described equipment was included in the flight test procedure. As previously indicated, only the sensors were flown and their outputs recorded on magnetic tape. The required computation was then performed on a ground-based, general-purpose computer programmed to accept inputs from the magnetic

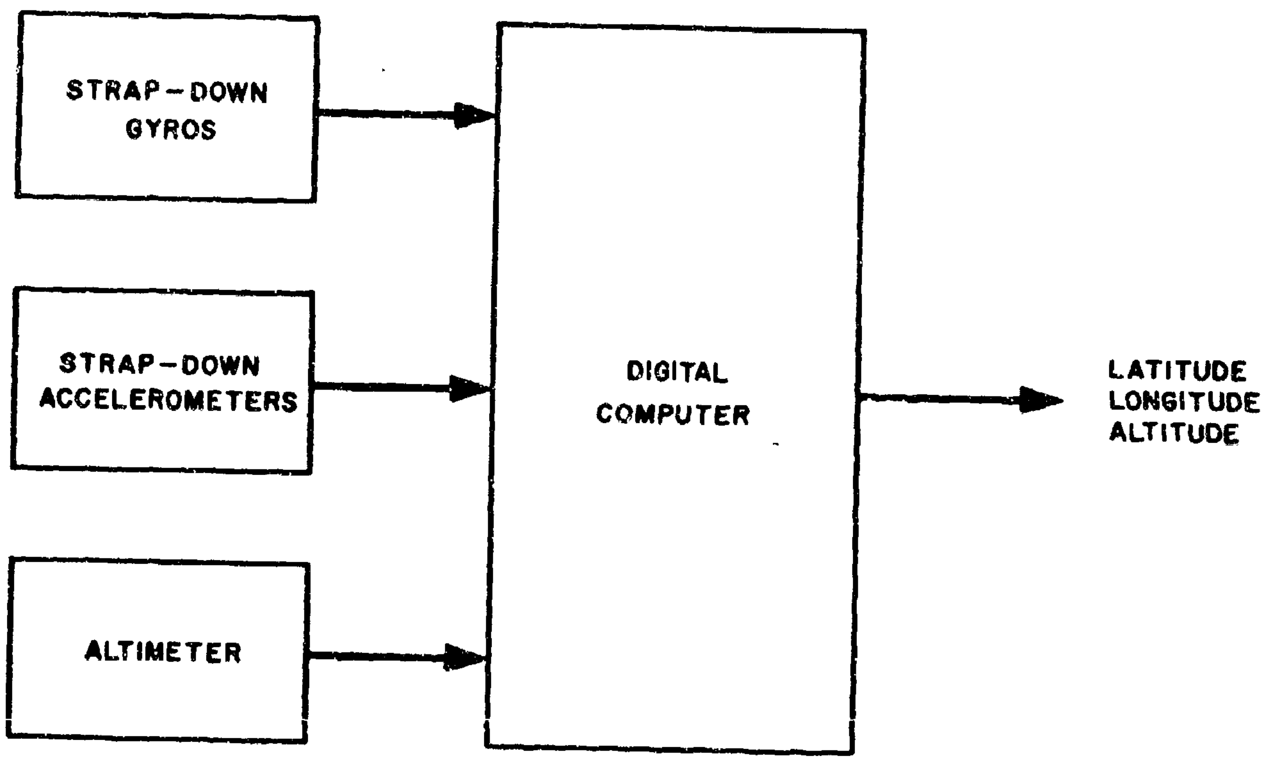


FIGURE 11. SELF-CONTAINED PURE INTEGRAL NO-GIMBAL SYSTEM, BLOCK DIAGRAM

on

tape and to perform the required computation. In conjunction with the recording process, an error correcting technique was utilized to prevent recording errors due to tape dropout and/or extraneous noise from occurring on the critical gyro information channels. This technique involved the generation and recording of parity information derived from the six gyro channels and the performance of a parity checking and error correction computation part of the computer program.

The computer used was an IBM 7090 equipped with a direct data connection. The direct data connection permits high-speed real-time data, which is n' generated synchronously with the computer clock, to be accepted and operated upon by the computer.

This flight test procedure significantly advanced the program schedule since it did not require completion of the special-purpose computer, and eliminated any computer debugging and maintenance that might have been encountered if the computer were flown. In no way was the ability of the procedure to demonstrate system feasibility compromised.

The equipment comprising the flight test system is shown in the block diagram of Figure 12. (Figure 13 is a block diagram of tape reading equipment necessary for data processing.) In Figure 12, the sensor package is energized with 400-cps power from both the aircraft supply and from an invertron. The latter power is precisely regulated in voltage and frequency as required for the gyro spin motors and the drift compensation circuitry.

The outputs of the sensor package are in the form of pulses generated randomly in time. These outputs, as well as similar outputs from the altimeter, serve as the inputs to the synchronizer and parity generator. This unit has the following three functions:

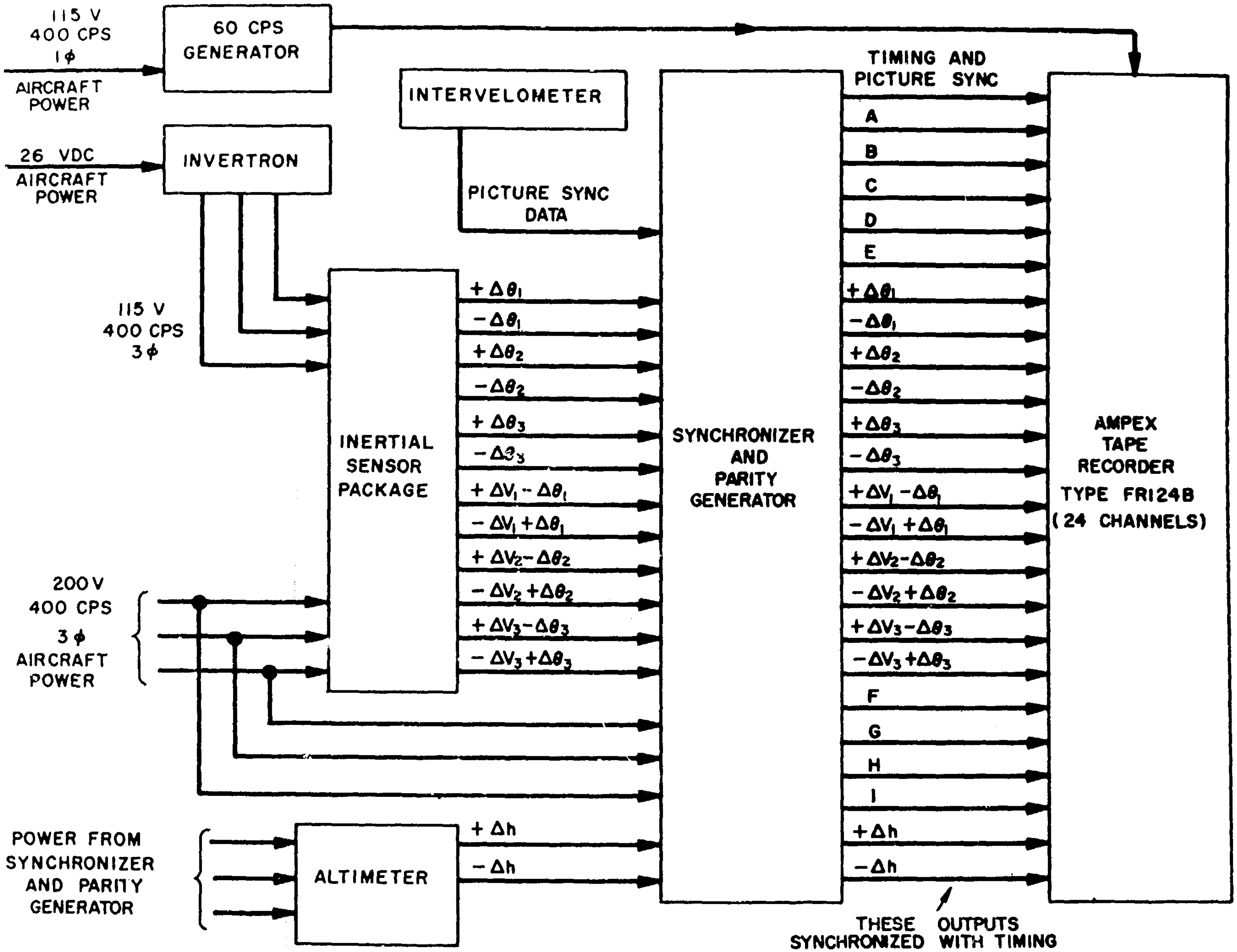


FIGURE 12. NO-GIMBAL FLIGHT TEST DATA RECORDING, BLOCK DIAGRAM.

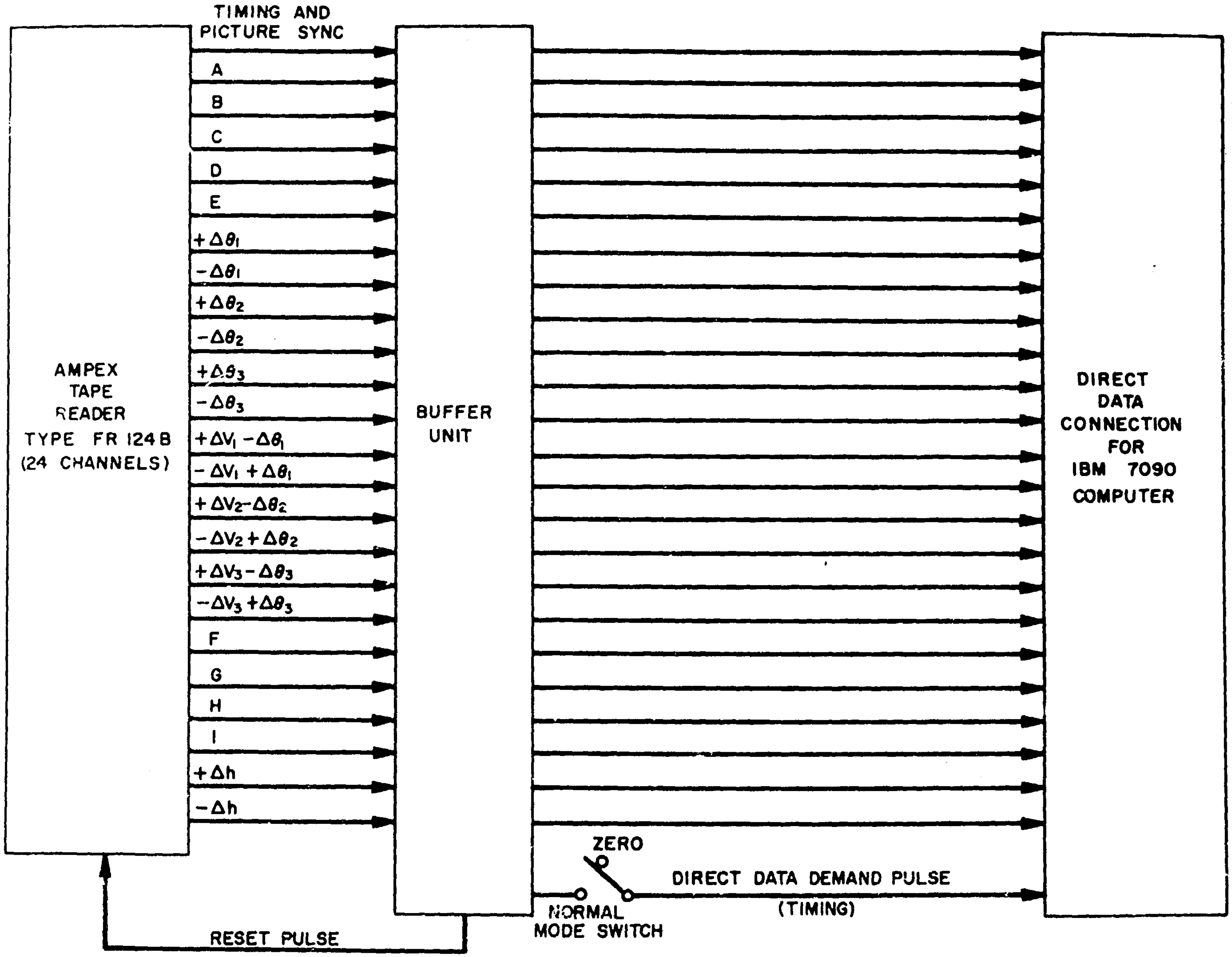


FIGURE 13. NO-GIMBAL FLIGHT TEST DATA PROCESSING, BLOCK DIAGRAM.

(1) synchronization of all data pulses; (2) generation of eight parity bits in accordance with a double error correction code for the attitude data ($\Delta\theta$'s); and (3) generation of a single parity bit in accordance with a single error detection code for acceleration and altitude data. The synchronizer and parity generator provides an output pulse at 350 μsec intervals on every output data line for which an input pulse was supplied during that interval, and also supplies pulses on the proper parity output lines for the given input data. In addition, a timing pulse is supplied every 350 μsec. Hence, a complete data word and a timing reference bit is written on the tape at this rate.

The equipment required for processing the flight tape is shown in the block diagram of Figure 13. When reading the tape, resynchronization of data is required due to tape skew. The buffer unit resynchronizes the tape reader outputs and generates a direct data demand pulse that controls computer operation. In addition, the impedance and amplitude levels of the tape reader are transformed to make them compatible with the requirements of the direct data connection. The buffer unit also generates a reset pulse, which clears the output translators of the reader, at the conclusion of each data word.

B. Inertial Sensor Unit

The inertial sensor unit consists of two enclosures mounted to a single shock and vibration isolator (see Figure 14). The larger enclosure, or sensor package, houses a cube-shaped frame that supports the inertial sensors, electronics, and other auxiliary equipment. The inertial sensors (three rate integral gyros and three pendulous integrating gyroscopic accelerometers) are mounted so that their input axes form an orthogonal triad. The temperature of the air within the enclosure surrounding the inertial

FIGURE 14. INERTIAL SENSOR UNIT

components is controlled to obtain maximum performance from the gyros and accelerometers. Bot these components are temperature sensitive, and their drifts are affected by temperature variations.

The smaller enclosure serves as a control unit with various switches, meters, and test points located on the front surface. The control unit is pictured in Figure 15. The upper row of switches is for turning on the various inertial sensor unit components and subsystems. Immediately below are three similar subpanels, which contain switches and potentiometers for performing drift tests and applying the drift compensation computer constants to each of the three rate integral gyros. Below the three subpanels are miscellaneous test points, auxiliary outlets, connectors, and gages.

C. Altimeter

The altitude sensor for the breadboard system is a Kollsman synchro type 1827-01 barometric altimeter. The analog output of the unit is converted to digital form by servoing a digital encoder to the electrical signal output. A mechanical differential and counter enable meteorological and instrument error corrections to be made on the unit. The altimeter is shown in Figure 16.

D. Synchronizer and Parity Generator

The synchronizer and parity generator first synchronizes all incoming data, i.e., it accumulates the incoming data in a given interval and transmits the correct information word at the conclusion of that interval. In addition, the unit determines the correct parity arrays for this data, and transmits parity information for each data word. The word interval (350 μsec) is short enough to ensure that no two information pulses will occur during the same word interval. Timing is derived from a precise crystal

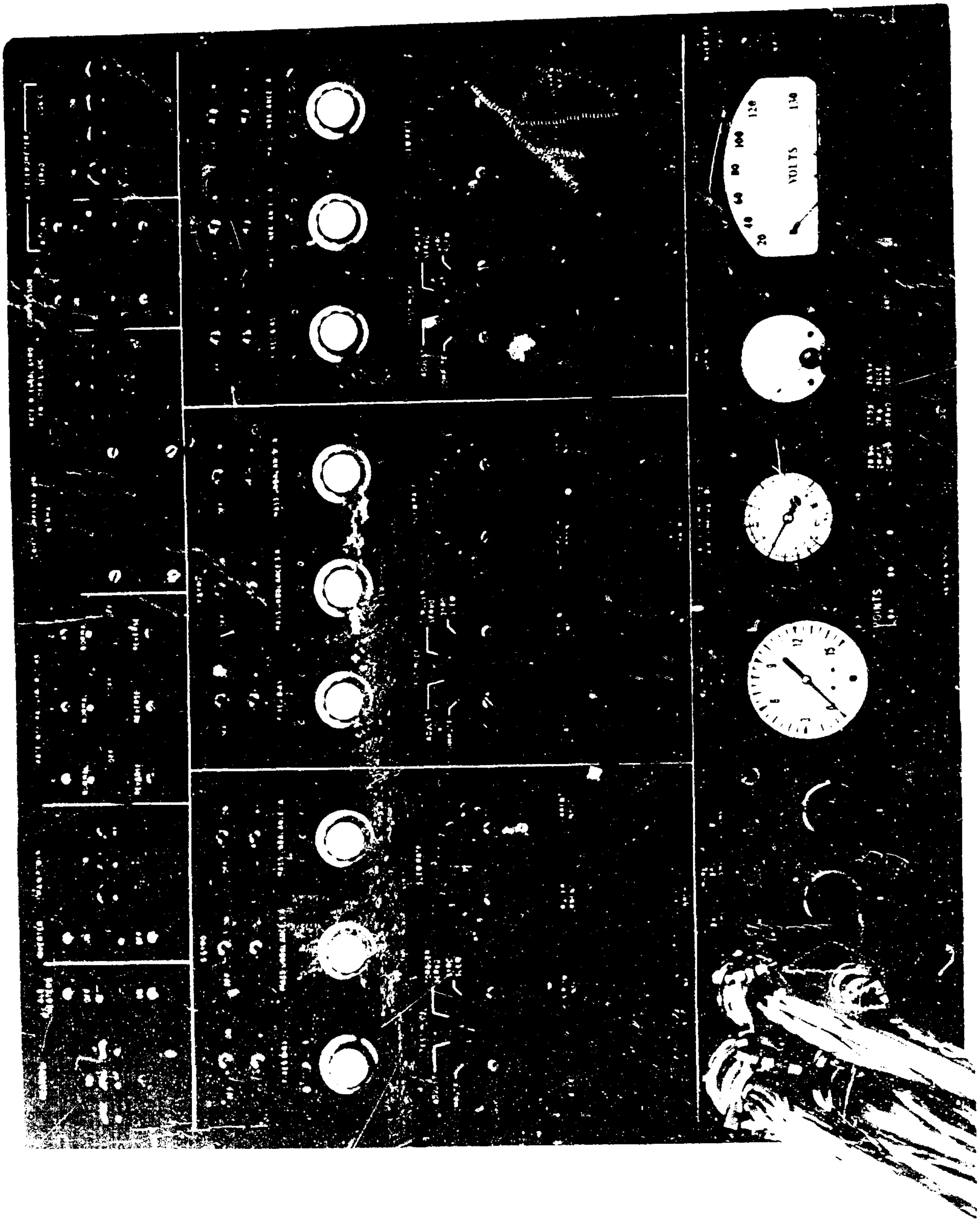


FIGURE 15. CONTROL UNIT

FIGURE 16. ALTIMETER WITH COVER

oscillator accurate to 1 part in 10^6. Each synchronizing circuit is composed of two stages of flip-flop storage to ensure that no incoming information is lost during reset of the synchronizer at the conclusion of the word interval.

The entire unit is built on a chassis that may be mounted into the tape recorder rack (see Figure 17). The drawer slides permit the unit to be extended out of the rack and rotated to any convenient angle for ease of maintenance.

E. Tape Recorder

An extensive investigation conducted during the development phase of the program indicated that no airborne tape recorders of sufficient capacity (number of channels and length of tape) were available to meet the flight test requirements. As a result, a laboratory type tape transport was selected since this type of unit had been successfully operated in an aircraft. Special precautions were taken to ensure that the machine would not be exposed to any extreme conditions that would exceed its capability. Since there was no temperature problem in the aircraft, the major environmental concern was that of vibration. A special shock and vibration mount was used to limit the degree of vibration transmitted to the unit to suitable values.

The transport handled 1 inch wide by 14 inch diameter tape reels. A special 24-channel read/write head was used to permit recording of all necessary data and parity information. Recording was performed at a tape speed of 5 inches per second that resulted in a total running time of 4.5 hours. This, in turn, resulted in a bit packing density of 600 bits per inch (nonreturn to zero recording). Recording at this high density caused the effects of tape skew to be rather pronounced; i.e., it was possible for information bits that were recorded during a given clock cycle to be read out at a time

corresponding to the preceding or succeeding clock cycle. However, the degree of skew was not severe enough to interfere with data processing. The transfer of information from one word to the next has a completely negligible effect upon the result of the computation performed on this information. Furthermore, when this effect occurs on bits corresponding to gyro or gyro parity information the double error correction process will effectively restore the "misplaced" bits to their original position (if no more than two bits are involved, which, as experience proved, was the case).

A separate tape unit was used for reading the recorded information since it was not practical to transport the recorder back and forth between the flight test site and the computer facility. The transport used for data processing at ASD was similar to the one used for recording except that it did not have a write capability. The 24-channel read head for the second machine was precision manufactured to match the skew pattern of the original write head, and was hand fitted to the second machine using a test tape made from the recording machine. The resultant static skew obtained from the combined operation of the two machines was quite small (less than 30 μsec at 15 inches per second).

F. Buffer Unit

The buffer unit function is to transform the output translator voltage levels (+12 volts for a "1" and -12 volts for a "0") from the tape recorder to the current signals required by the direct data connection, 0 milliamp for a "1" and -6 milliamps for a "0." In addition, the buffer provides the timing pulses (direct data demand and reset) required for proper transfer of information between the tape reader and the computer.

Incoming translator signals are clamped to levels generated from precise, series-regulated bias voltages. The driver circuits that transform the information from voltage to current levels have low impedance in the "0" state, thus tending to minimize noise into the direct data connection. Tape noise or dropout on the timing channel does not affect the direct data demand pulse because tape timing is used to synchronize the free running buffer timing circuits. The direct data demand pulse is designed to be within tolerable timing limits for as many as two dropouts of input timing pulses. Noise pulses are filtered out by the multivibrator.

All power supplies are regulated and filtered to eliminate cross coupling and effect of outside power switching. Electronic circuits are either on circuit cards or of the module type. The entire unit is built on a chassis that is mounted into the tape reader rack in a similar manner to the synchronizer and parity generator. The drawer slides permit the chassis to be extended out of the rack and rotated to any convenient angle for ease of maintenance. The buffer unit, after removal from the tape reader, is shown in Figure 18.

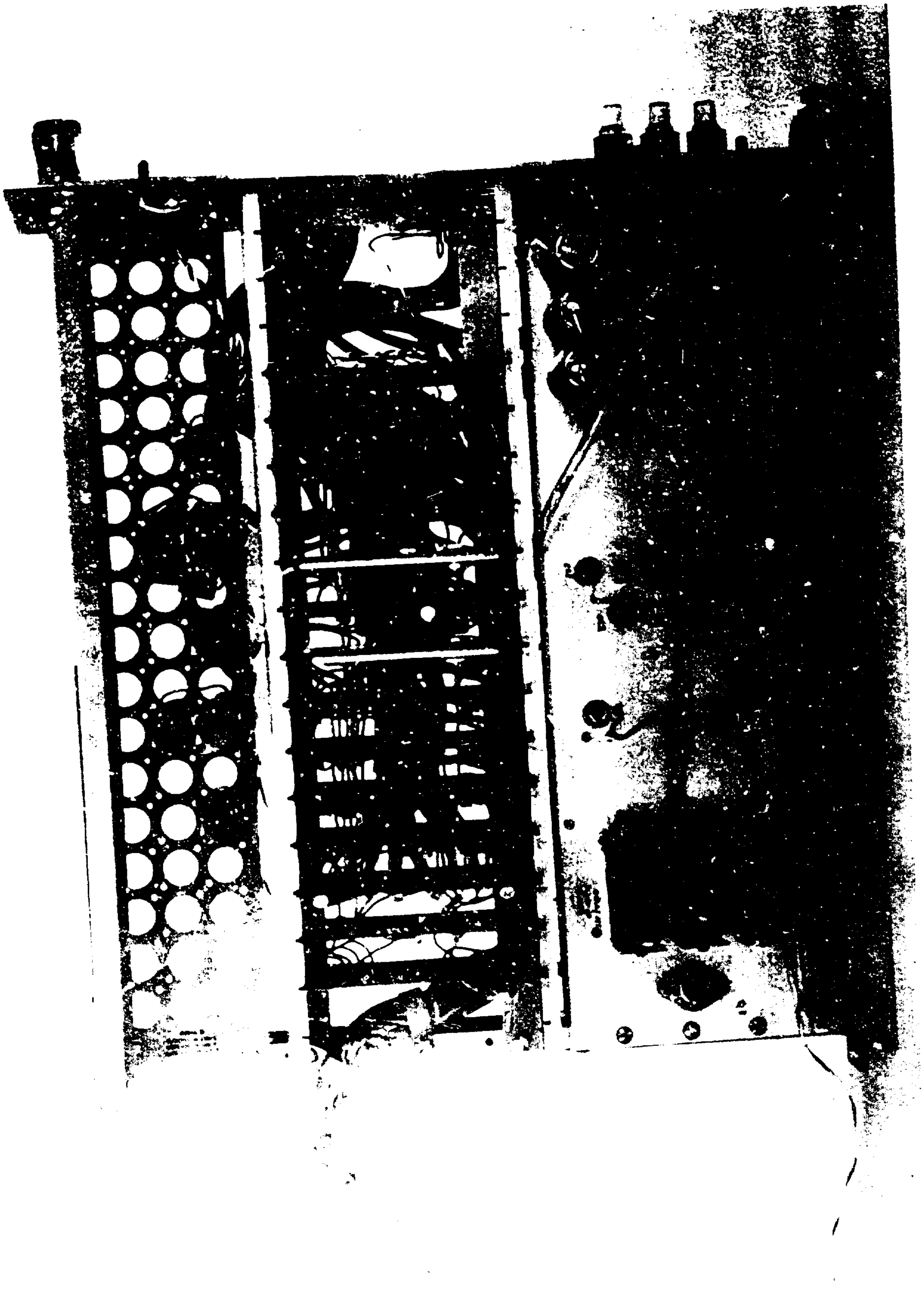


FIGURE 18. BUFFER UNIT REMOVED FROM TAPE READER

V. DESCRIPTION OF FLIGHT TEST PROGRAM

A. Equipment Design and Procurement

The major equipment required for the flight test program is the inertial sensor package. This unit was previously fabricated and tested on development contract AF 33(616)-6734. In addition, the altimeter and the FR-124B tape recorder were also fabricated or procured during that effort. As a result, a minimum of additional equipment was required to conduct the flight test program. Most of the new hardware developed under the present program was auxiliary equipment required to permit proper interconnection of the system with the tape recorder and IBM 7090 computer. In addition, equipment such as power supplies, camera, and theodolites were required. The following paragraphs describe in detail the new equipment fabricated or otherwise procured during the flight test program.

1. Design of Synchronizer and Parity Generator. Reference should be made to Figure 12 (which is a block diagram of the flight test recording system), and to Figure 19 (which includes a block diagram of a portion of the synchronizer and parity generator). The sensor outputs that are fed into the synchronizer and parity generator consist of voltage pulses, each pulse representing an incremental quantity of measured information. The outputs are referred to as either a "1" or "0" corresponding to the presence or absence of a pulse. The pulses are generated randomly in time; i.e., they occur nonsynchronously and at random intervals with respect to a time reference. Parity checks are performed on all sensor outputs, and parity bits are generated in accordance with a Hamming code. A double error correction code is used on the gyro outputs, and a single error detection code is used on the accelerometer outputs.

In order for parity information to be computed properly, it is first necessary to synchronize the data. This is accomplished in a synchronizer where all pulses, which occur on the sensor lines during a fixed time interval, are synchronized. This time interval is sufficiently small to prevent more than one data pulse from occurring during the interval (in this case 350 μsec). The parity generators then operate upon the synchronized data and generate the proper parity bits.

Table 3 indicates the rules by which the gyro parity bits are generated. Parity bit "A" performs an odd parity check on data in channels containing $+\Delta\theta_1$, $-\Delta\theta_1$, $-\Delta\theta_2$, and $-\Delta\theta_3$ as indicated by "X" in Table 3. Similarly, the table indicates the gyro lines that are checked by the remaining parity channels. "Performing an odd parity check" means that the parity bit is assigned a value of "1" or "0" depending upon whether the number of "1"s on the corresponding data lines is even or odd, respectively. For example, if only data lines $+\Delta\theta_1$ and $-\Delta\theta_2$ contain a pulse during a given interval, parity channels, A, D, and H would be set equal to 1, and channels B, C, E, F, and G would be set to 0. The parity bits are recorded, along with the information bits, on tape. When the data is played back, the information is resynchronized to eliminate the effect of tape skew, and the parity conditions are again checked. The sum of "1"s on each parity channel and its associated data lines must be odd or that parity check fails. It is important to note that any single or double error on any of the parity lines or data lines or combination thereof provides a unique combination of parity checks that fail. Thus, for example, a single error on data line $-\Delta\theta_1$ causes failures on parity checks A, C, E, F, and G. Similarly, a double error on $+\Delta\theta_1$ and $-\Delta\theta_2$ causes a failure on parity checks B, C, E, F, and G. In each case, no other combination of single or double errors in writing or reading the recorded information can result in the same combination of parity check failures. The code of Table 3 is constructed

Table 3. Parity Code for Double Error Correction of the 6 Attitude Gyro Information Bits

Parity Bits	Attitude Gyro Bits					
	$+\Delta\theta_1$	$-\Delta\theta_1$	$+\Delta\theta_2$	$-\Delta\theta_2$	$+\Delta\theta_3$	$-\Delta\theta_3$
A	X	X		X		X
B	X		X		X	X
C		X		X	X	X
D	X		X	X	X	
E		X	X	X		X
F	X	X	X		X	
G	X	X				
H					X	X

in a manner so that this uniqueness of indication holds. During the system computation, the particular combination of parity check failures is examined, and the bits thereby indicated to be in error are inverted (a "1" is changed to a "0" and vice versa) to achieve the desired correction.

An additional parity bit "I" performs an "odd parity check" on the 6 acceleration and on the 2 altitude bits. If the parity check on these channels fails on playback, it is known that a single or odd number of errors exist on the 9 channels. Since these channels are not as critical as the gyro channels, a nominal amount of errors is tolerable. However, it is important to know whether a catastrophic error, such as complete dropout of a channel, has occurred. The single error detection scheme is sufficient to indicate such an occurrence.

A schematic diagram indicating the generation of the "A" parity bit is shown in Figure 19. Gyro channels $+\Delta\theta_1$, $-\Delta\theta_1$, $-\Delta\theta_2$, and $-\Delta\theta_3$ feed into their respective synchronizers S1 to S4. At some short time prior to time T_w (the instant when writing occurs), the output of each synchronizer is set by a set pulse to its correct value for that word. The synchronizers are directly coupled to a chain of "exclusive - or" gates (G_1 - G_4) in the "A" parity generator. This type of gate has a "1" output when one and only one of its inputs is a "1." Thus, it may be seen that the input to inverter I_1 will be at the "1" level if there is an odd number of "1" inputs to the parity generator. The output of I will be "0" in this case. Conversely, the output of I will be "1" for the case where there is an even number of "1" inputs. Each variable energizes one input of its output "and" gate, the other input of each gate being energized by a pulse that occurs at T_w. These gates feed the tape recorder write inputs. Hence, at time "T_w," the correct parity and gyro information is available for transmission to the computer. A short

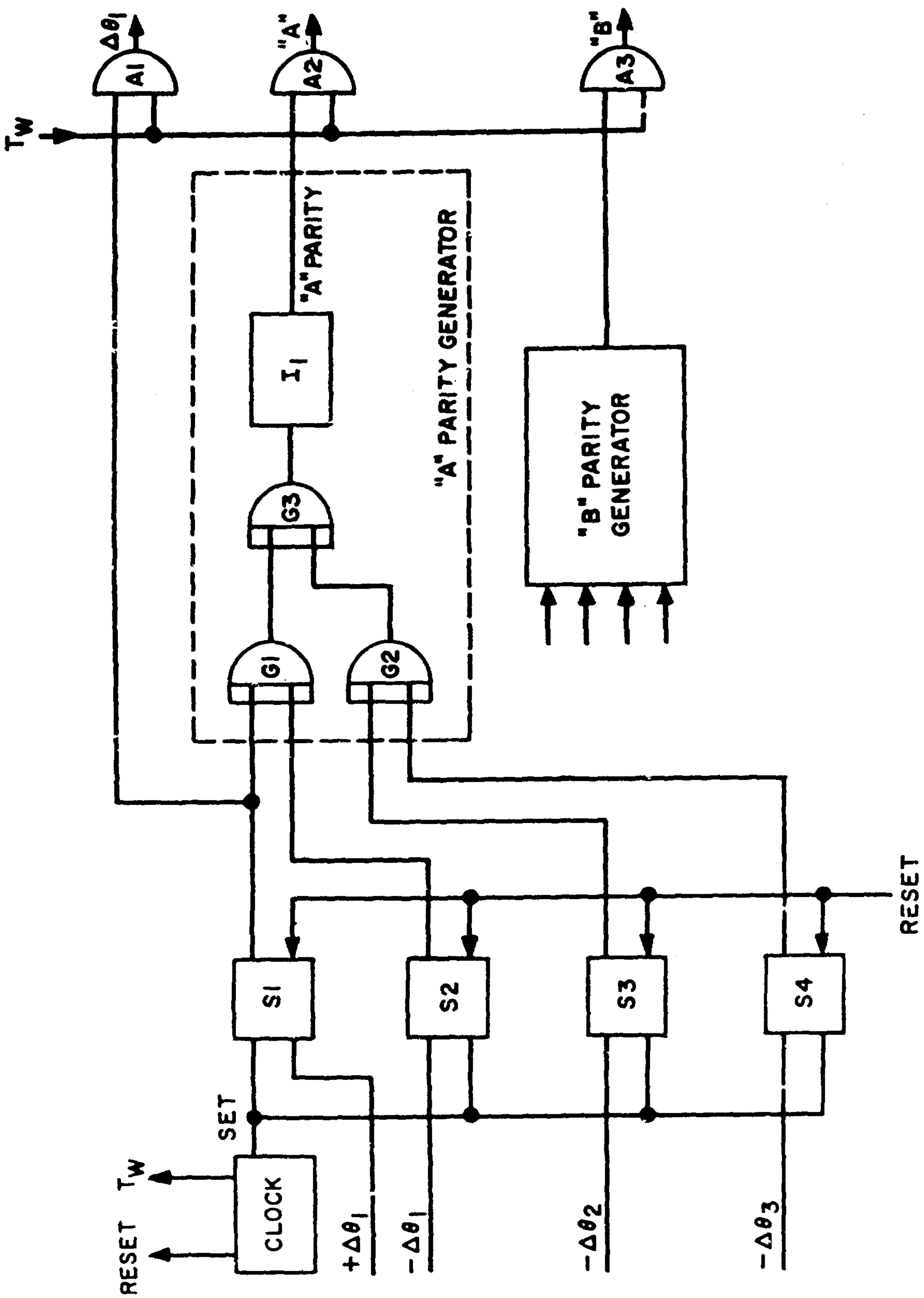


FIGURE 19. GENERATION OF "A" PARITY BIT

time after "T_w," the clock sends out a reset pulse that clears all the synchronizers. The other parity bits are generated in a similar manner.

2. Buffer Unit. The flight test data, recorded on 24-channel tape, was processed on the IBM 7090 computer facility at ASD. This computer had been modified by the addition of a direct data connection to enable it to accept information from a high-speed, nonsynchronous external source. In order to make the tape recorder output compatible with the direct data connection, certain buffering and logical circuitry were required. This circuitry was incorporated into an additional unit called the buffer.

The buffer unit receives a 24-bit word from the tape reader every 117 μsec (nominally). Each bit of the word is in the form of either a "0" or a "1" as represented by the voltage level of a flip-flop. These flip-flops must all be reset to 0 after the word has been transferred to the IBM 7090 computer.

The direct data connection requires a direct data demand current pulse to enable it to receive the word. This control signal is generated by the buffer, which in addition, converts the voltage level outputs of the tape reader to current levels as required by the computer.

Figure 20 shows typical operating wave forms and timing. An output of the timing channel of the tape recorder occurs every 117 μsec as shown in Figure 20A. The timing of the leading edges of the outputs of all the other channels will vary from that of the timing channel due to machine skew. This is indicated by the dotted lines in the diagram. The buffer unit generates a -6 milliamp direct data demand pulse as shown in Figure 20C, which transfers the word into the direct data connection 58 μsec later than the largest possible skew variation. A short time after the direct data demand pulse

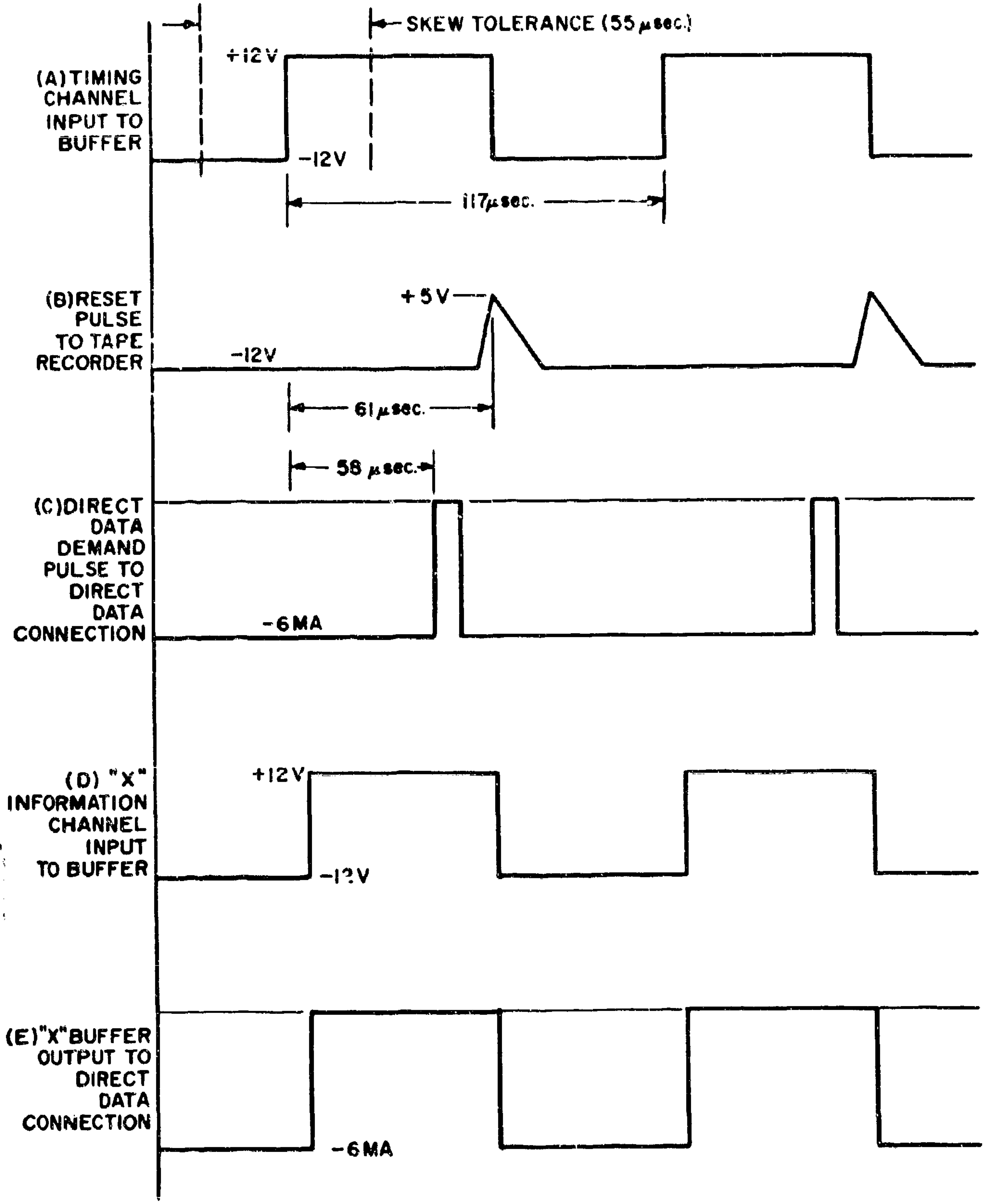


FIGURE 20. INPUT AND OUTPUT WAVEFORMS TO BUFFER UNIT

(3 μsec), a reset pulse is generated. This pulse resets all the tape reader flip-flops to 0 (Figure 20B). Figure 20D shows the form of the voltage level input to the buffer, and Figure 20E shows the current level output of the buffer to the direct data connection.

Figure 21 shows a block diagram of the buffer unit. All of the information channels (23 total) feed directly into clamping and level shift circuits and then into buffer circuits. The buffer circuits transform a voltage signal to the current signal required by the direct data connection. The 24th channel (the timing channel) feeds into the pulse shaping circuitry (a clamp and a monostable flip-flop). The output of this circuitry synchronizes the output of a free running multivibrator (M. V. 1) to the actual frequency of the tape information (the leading edge of the timing level). The multivibrator output is then delayed in a monostable (one shot) multivibrator (O. S. 2). The output of O. S. 2 is reshaped in a blocking oscillator (B. O.), and then applied to the clamping and buffering circuits to form the direct data demand pulse required by the direct data connection. A second output of the blocking oscillator is given an additional 3-μsec delay. This delayed output is amplified and shaped in the reset amplifier, and is then used to reset all of the tape reader flip-flops.

3. Miscellaneous Equipment. Some additional equipment was required to perform the flight test of the No-Gimbal System. This equipment was obtained as GFE where possible, and was purchased when it was not available from Government stores.

The equipment consisted of the following:

a. Fairchild T-11 Camera

b. Ampex FR-124B Tape Reader

c. Leland MGE-37-2 Inverter

d. Wild T2 Theodolites

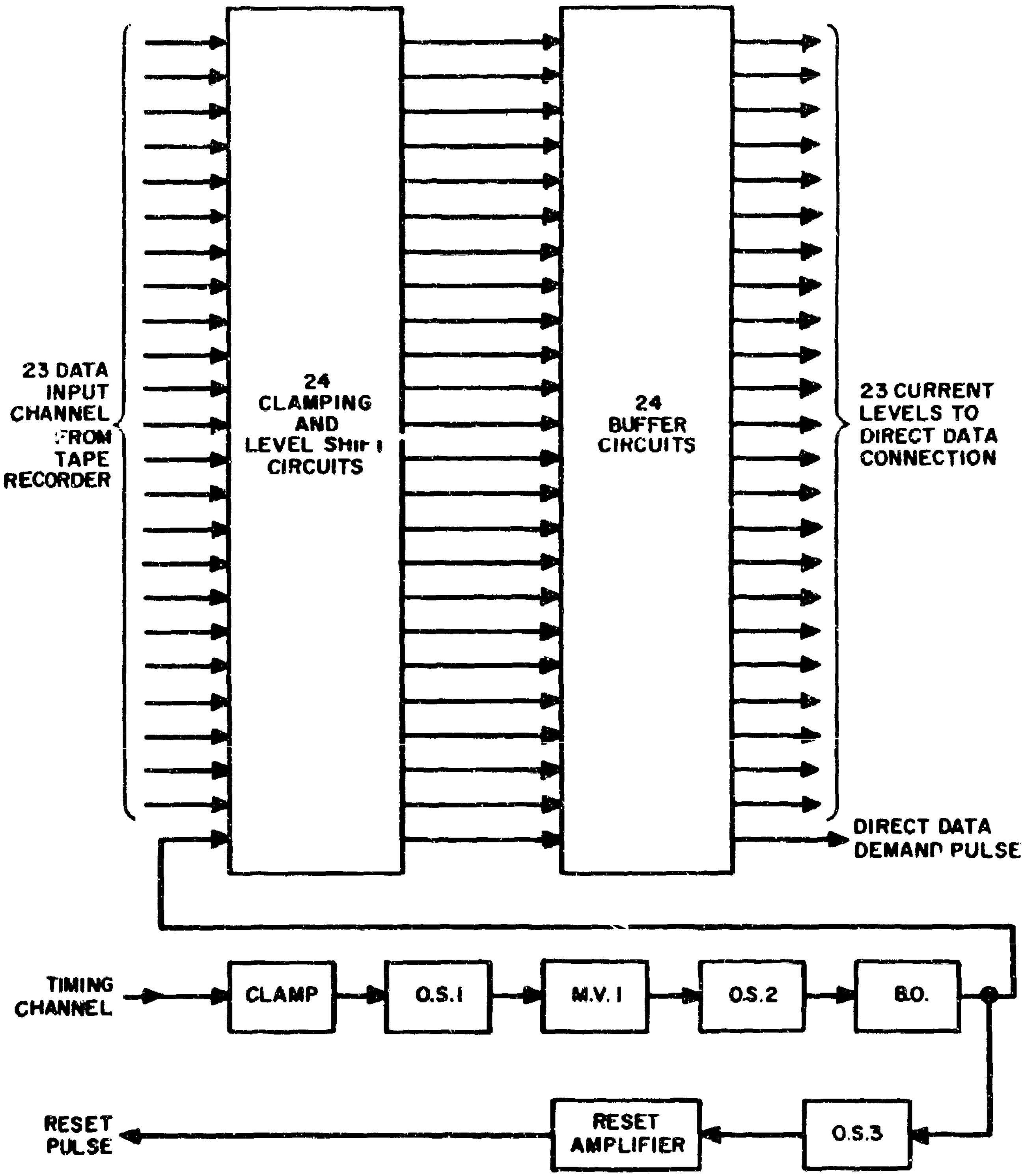


FIGURE 21. BUFFER UNIT, BLOCK DIAGRAM

Fairchild T-11 Camera. A Government-furnished T-11 aerial camera was used to provide photographs of the ground for position fixing. The camera was triggered automatically by a B-9 intervelometer at 2 minute intervals to provide an adequate number of photographs.

Ampex FR-124B Tape Reader. An FR-124B tape reader was purchased from Ampex, and was used at ASD as playback equipment. The unit consists essentially of a transport unit with a 24-channel read head and its related electronics.

Leland MGE-37-2 Inverter. The Ampex FR-124B Tape Reader, which was installed in the aircraft, required 115-volt 60-cps power. Since the aircraft did not contain this type of power, it was necessary to provide an inverter. The Leland MGE-37-2 Inverter is capable of producing 115-volt 60-cps ± 5 percent, 1 kva for the 19-volt dc to 30-volt dc variation expected in the aircraft.

Wild T2 Theodolites. As indicated in a separate section of this report, it was necessary to accurately align the trunion axis of the tilt-turntable in an east-west orientation. Two Wild T-2 Theodolites were used to perform the alignment. These items were supplied as GFE.

B. Laboratory Testing

Several tests necessary to insure satisfactory operation of various portions of the system prior to flight testing were performed in the laboratory. These are described below.

1. Tape Dropout Tests. One of the most critical aspects of the flight test procedure involved the quality of the magnetic tape used for data recording. Magnetic tape is prone to so-called dropout resulting from imperfections in the oxide coating on

the tape or from dust that causes the tape to be lifted away from the write head during recording. Pretested tape was not available from any manufacturer in the reel size used (14-inch diameter), and, therefore, it was necessary to perform pretesting at Ford Instrument Company. Test equipment was developed to detect dropout and pickup resulting from the tape and from tape recorder operation. To detect tape dropout, each tape was recorded at a 350 μsec rate with all "1" information. The tape was then played back into the test circuitry. Counters, which were energized by the test circuitry, would then indicate the number of occurrences of single, double, triple, or additional dropouts on the tape. The same circuitry when used in complementary fashion, detected pickup emanating from a tape that was recorded with all "0" information. This testing program detected several reels of tape that had major surface imperfections (causing multiple dropouts in a given word); it also indicated that the tape recorder did not erase tapes completely, and that certain tape recorder components were noisy. As a result of this, additional filtering was added to reduce noise, and all tapes were degaussed before being used for flight test recording.

2. Interconnection of Flight Test Equipment. All equipment to be used in flight testing (sensor package, synchronizer and parity generator, tape recorder) was connected together in the laboratory. The sensor package was then energized, inputs were applied to each sensor, and outputs were recorded. The output of each sensor was then checked by reading the tape. During preliminary testing, it was found that the outputs as read from the tape were inaccurate and did not correspond exactly to the outputs of the sensor package. The discrepancy was due to noise. This was corrected by rerouting the system grounding, and shielding the signal leads between the synchronizer and parity generator and the tape recorder.

3. Interconnection of Data Reduction Equipment. Prior to the start of flight testing, all equipment to be used for flight test data reduction was connected together at the ASD computer facility. This equipment included the tape reader, the buffer unit, and the IBM 7090 computer. Test tapes were especially constructed with various patterns of bits, and programs were devised to print out the taped information on the IBM printer. Initially, some difficulty was encountered due to radiated and cond[illegible]d noise. Rerouting of ground returns and addition of decoupling networks to the tape recorder output translators overcame this difficulty.

C. Equipment Installation and Alignment

The primary considerations in installing the equipment in the aircraft and at the airfield were as follows:

1. To provide a sheltered area so that drift compensation and package alignment could be performed under favorable conditions.

2. To install the tilt-turntable on a solid concrete base with the trunion axis aligned east-west.

3. To provide an expeditious method of removing the sensor package from the tilt-turntable to the aircraft and back again without exceeding the rotational rates of the system.

4. To mount the sensor package so that it would be maintained relatively level during flight in order to reduce gyro drift due to anisoelastic effects. Since the aircraft floor was tilted approximately 8 degrees from the horizontal during flight, it was decided that a rigid mounting base for the sensor package would be provided, which would compensate for this tilt.

5. To locate the equipment and interconnecting cables so as to minimize noise in the vicinity of the tape recorders and sensor package.

6. To provide adequate shockmounting, where required, to assure proper operation of all airborne equipment.

The tilt-turntable was located in a hangar that was large enough to house the aircraft, and in a position such that the sensor package could easily be transferred from the table to the aircraft. The hangar floor (which was designed to support the weight of an aircraft, and constructed of concrete nearly one foot thick) provided an adequate base for the turntable.

Alignment of the tilt-turntable was required in order to perform drift compensation and to initially align the sensor package. The table was aligned with its trunnion axis east-west and with the table surface perpendicular to the local vertical. East-west alignment was accomplished with the aid of two Wild T-2 theodolites and an adjustable face mirror mounted to the table. The adjustable face mirror was positioned so that its face was perpendicular to the trunnion axis of the table. Azimuth bench marks were then transferred to the desired location of the tilt-turntable through the use of theodolites. Autocollimation into the adjustable face mirror was then used to align the trunnion axis. Levelness of the table top was achieved through the use of precision levels and three adjustable jack screws at the base of the tilt-turntable.

Four stops on the tilt-turntable provide for the alignment of the sensor package to north, south, east, or west orientations. These stops were set by aligning the sensor package with a reference surface (porro prism) facing east, and then setting the first stop. The sensor package was then removed and a theodolite accurately mounted

over the center of rotation of the table. A distant target was then selected and the theodolite was set to 0 degree. The remaining stops were set by rotating the table and then indexing the theodolite 90 degrees, 180 degrees, and 270 degrees while sighting the distant target.

A fork-lift truck was used to transport the sensor package to and from the tilt-turntable. During this operation, the sensor package shockmount was uncaged so as to attenuate any rotational rates due to motions of the truck. In order to eliminate high rotational rates when mounting the package in the aircraft mounting base, the following procedure was used. A rod located on one end of the sensor unit was lowered into a cradle on the mounting base thereby creating a pivot joint. The other end was supported by a hand hoist and slowly lowered on to the mounting base that is 8 degrees off the horizontal when the aircraft is grounded.

Electrical noise problems were eliminated by locating power units, such as the invertron, remotely from the sensor unit and tape recorders. In addition, the cables were routed so as to minimize noise, and shielded leads were used when necessary.

Shockmounts were used on the sensor package, invertron, tape recorders, and altimeter to provide vibration and shock isolation.

D. Flight Test Procedures

1. Preflight Procedures. Prior to each flight test, a preflight test procedure was carried out. This consisted of drift compensation, accelerometer and gyro drift checks, and tape recorder functional checks.

The warmup and checkout procedure was begun approximately 8 hours before the scheduled take-off time. It consisted first of a 2-hour warmup period during which the sensor package temperature control system was turned on, followed by a 1.5 hour

period during which the gyros, accelerometers, and all electronics were energized. The entire package was allowed to soak until it reached an equilibrium temperature of 115°F so as to eliminate the effect of temperature variation on the drift of the components. At this point, gyro drift compensation, which required approximately 3 hours to complete, was performed. A complete description of the procedure followed during drift compensation is contained in ASD Technical Report 61-484. Upon completion of gyro drift compensation, a check was made on the drift rate of each gyro. This consisted of connecting the two output lines of each gyro (through the tape recorder) to a pair of electronic counters, and timing the pulses. Knowledge of the orientation of the gyro with respect to the earth rotation vector permitted the determination of the theoretical time, which should elapse for a given number of pulses. Deviations from this computed value were considered to be due to gyro drift.

The AB-4 gyroscopic integrating accelerometers are similar in construction to the rate integral gyro, and are also subject to drift errors. Prior to flight, the integrating accelerometers were also checked for excessive drift by a procedure similar to that employed in checking the rate integral gyros. Two of the accelerometers were checked in a zero-g field since they operated about this point during most of the flight. The third accelerometer, which measured accelerations along the vertical axis of the aircraft during flight, was checked in a 1-g field. A preset counter and eput meter were used for the latter test.

Deviations of the experimental results from the calculated value of elapsed time were a measure of drift.

If drift rates of either gyros or accelerometers were excessive, steps were taken to improve the drift. In the case of the gyros, drift was improved by repeating portions of the drift compensation procedure, and in the case of accelerometers, by adjusting the balancing screws.

The tape recorder was given a functional test before the start of each flight test. The purpose of the test was twofold; first, to make sure that all tape recorder channels were functioning properly, and second, to record a pattern on the tape for use during checkout prior to the playback procedure at the computing facility at ASD. The test consisted of recording pulses at a certain frequency on all 24 channels, and observing the voltage at each write amplifier with an oscilloscope. When it was determined that the tape recorder was operating satisfactorily, the breadboard used to record the pulses was disconnected from the synchronizer and parity generator, and the sensor package output cable was connected in its place. The altimeter was also connected at this time.

The sensor package was rotated about each of the three axes to generate sensor outputs that were observed with an oscilloscope. Similarly, the altimeter was slewed and the outputs observed at the write amplifiers. The purpose of this procedure was to check the continuity of each data line from the encoder to the write head. The synchronizer and parity generator was then put into the standby mode, the sensor package aligned, and the altimeter set to read ground altitude.

After a short period in standby, the flight test was initiated by switching the synchronizer and parity generator to "run." From this point on, all pulse outputs from the system were recorded. A fork-lift truck with special sling was used to load the sensor package aboard the aircraft. (See Figures 22, 23, and 24.) The aircraft was then wheeled

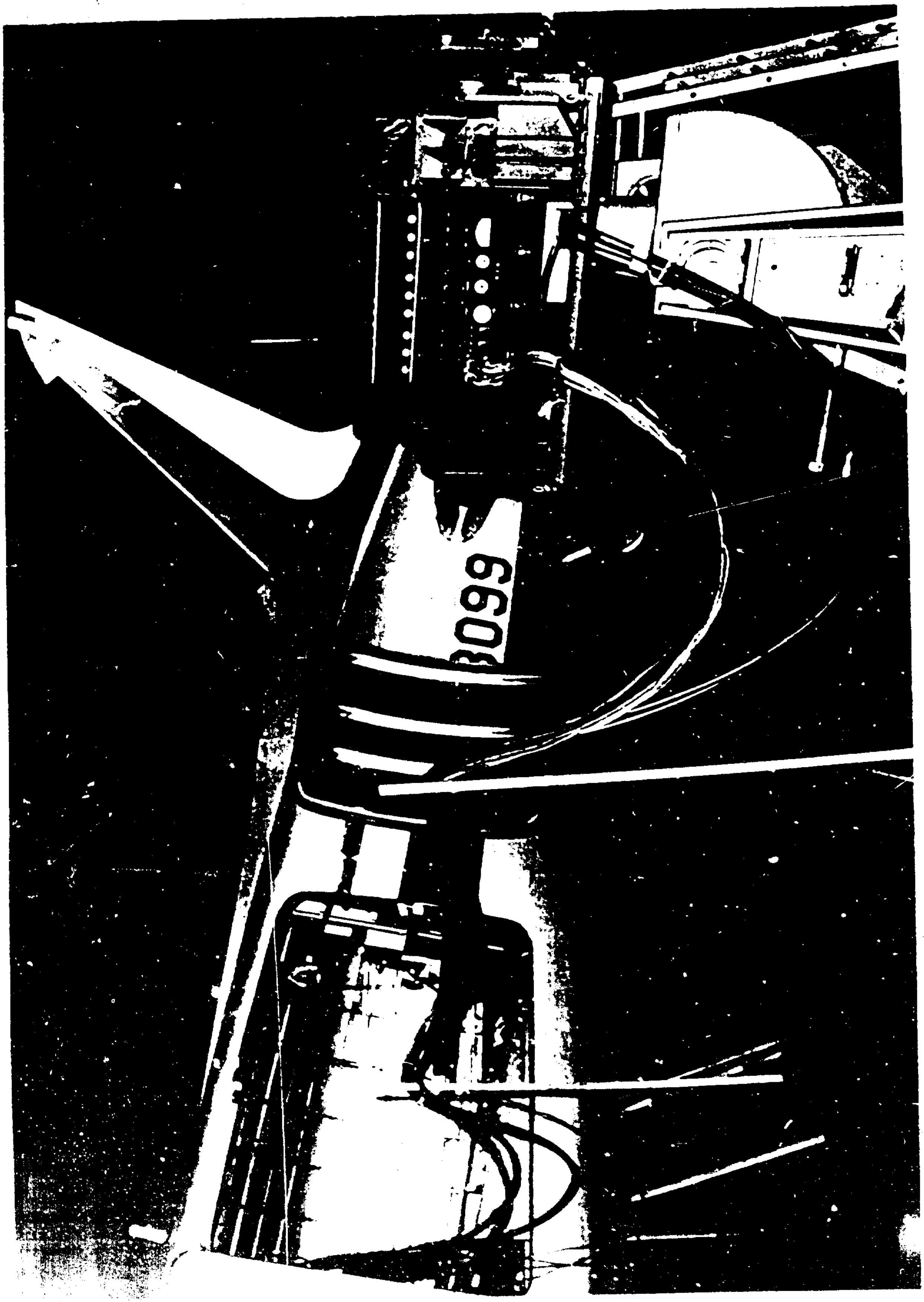


FIGURE 22. SENSOR PACKAGE ON TILT-TURNTABLE, ADJACENT TO FLIGHT TEST AIRCRAFT

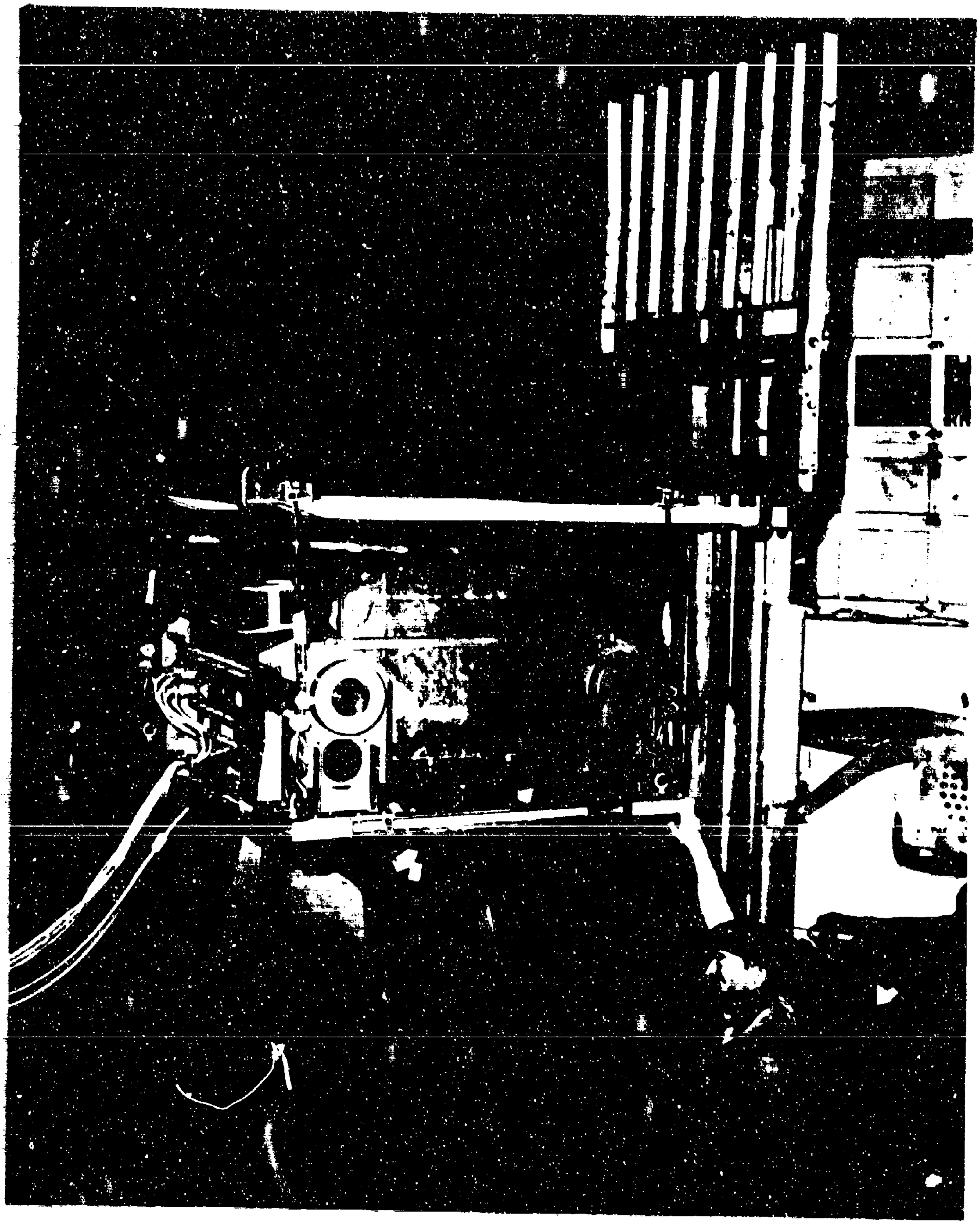


FIGURE 23. MOVING SENSOR PACKAGE FROM TILT-TURNTABLE TO FLIGHT TEST AIRCRAFT

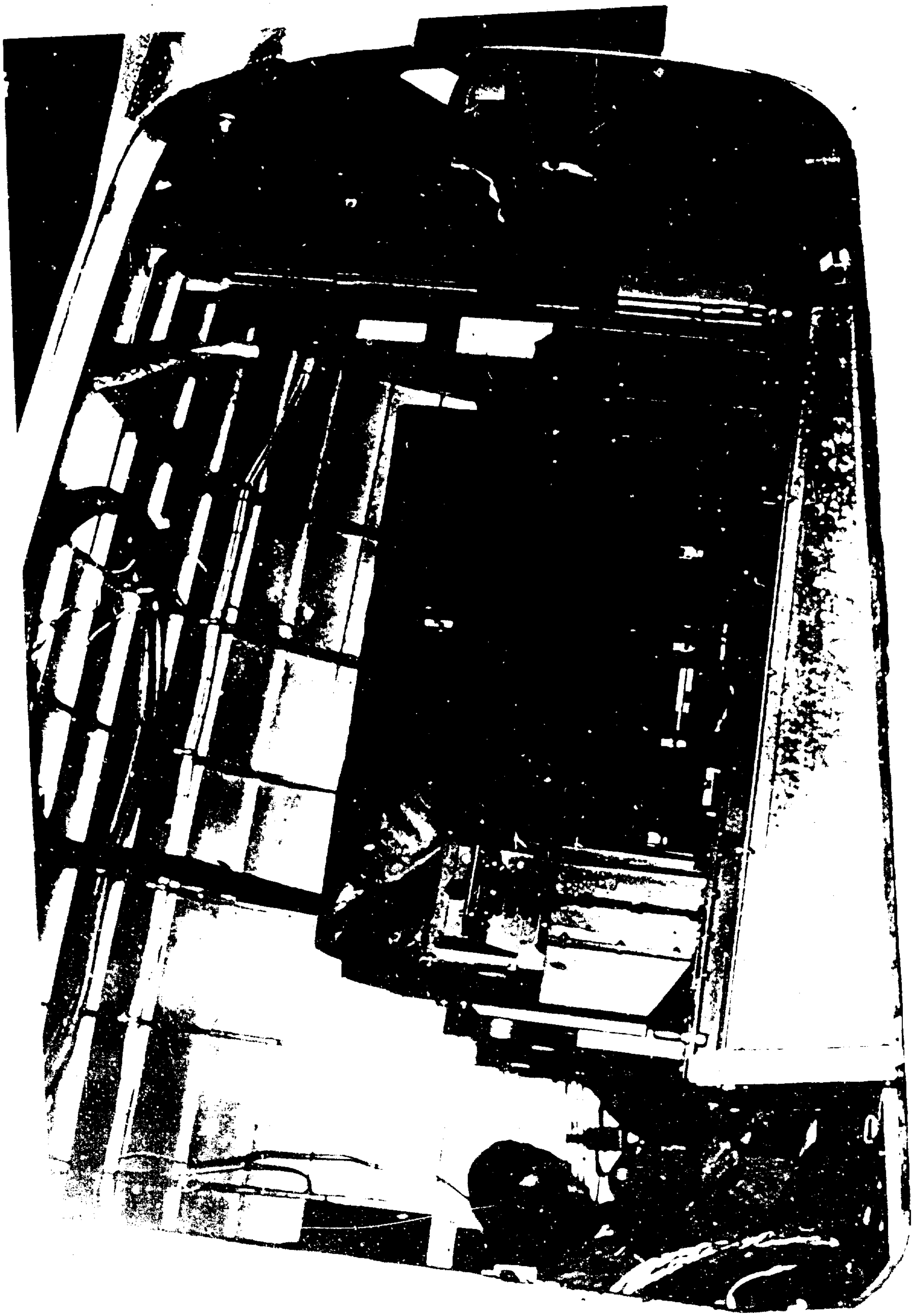


FIGURE 24. SECURING SENSOR PACKAGE TO MOUNTING BASE, PRIOR TO FLIGHT TEST

out of the hangar, and the engines were started. The aircraft generator and batteries were switched on the power line, and the ground power cart disconnected. Thus, the transfer from ground to aircraft power was accomplished without interruption as required by the system. The aircraft then taxied to the end of the runway for take-off.

2. Inflight Procedures. Immediately after take-off of the aircraft, the T-11 aerial camera, which provided photographs of aircraft position, was put into operation. Simultaneously with the ground photographs, a 35 mm camera took pictures of an instrument panel that provided information of aircraft altitude, roll and pitch, as well as time, frame number, and temperature.

These data were required for photointerpretation and subsequent comparison of actual and computed positions at various points along the flight path.

Upon reaching flight altitude, the altimeter was corrected for barometric conditions using ground data from the airport and outside air temperature. Except for large changes in altitude or barometric conditions, no additional altimeter changes were needed.

A multichannel brush recorder was used for continuous inflight monitoring of critical power supply voltages, such as the 28-volt d-c line, the 208-volt, 400-cps line, etc. During flight No. 8, maneuvers were performed to test system operation with high input rotational rates, and several channels of the brush recorder were used for recording the roll and pitch outputs from the aircraft's gyros.

3. Postflight Procedures. Upon landing, the ground power cart was connected to the aircraft thus enabling the pilot to turn off engines without disruption of power to the system. The aircraft was then wheeled back into the hangar and the sensor

package unloaded and reinstalled on the table. The purpose of this procedure was to compare computed attitude with actual attitude at the end of the test. The system was then shut down. The flight test tape was then inspected for catastrophic type failures, and prepared for processing at the IBM 7090 facility at ASD.

E. Computer Programming and Data Processing

The incremental outputs of the body-mounted sensor package, recorded on magnetic tape during each flight test, were later read into an IBM 7090 computer. The computer then determined aircraft position as a function of time of flight. Therefore, this large ground-based computer simulated the operation of an airborne navigation computer in a No-Gimbal System. In addition, it performed certain parity checks on the data to verify the accuracy of, and correct for certain errors in, the recording operation.

The IBM 7090 computer, at ASD in Dayton, Ohio, was used for the processing of the flight test data. This computer was equipped with two data channels for data input from peripheral equipment. To one of these data channels, a direct data connection was made, which enabled a direct connection from external equipment to the data buffer register in the data channel. By supplying the proper logical signals on the control lines for the data channel, it was then possible to feed 36-bit data words in parallel directly to this buffer register, and through it, to the main memory of the computer. It was this special high-speed data input capability that made possible the reading of the densely packed magnetic tape records of the flight test data.

These recordings of flight data took the form of 24-bit words written in parallel on 1-inch wide magnetic tape. The information contained in each of these data words is specified in Table 4. Each word was read in parallel through the direct data

Table 4. Tape Recorder Format

Tape Recorder Channel	Information Bit
1	$+\Delta\theta_2$
2	$-\Delta\theta_2$
3	$+\Delta V_2$ $-\Delta\theta_2$
4	A
5	Timing and Picture Sync
6	$+\Delta\theta_3$
7	$-\Delta\theta_3$
8	$-\Delta V_2$ $+\Delta\theta_2$
9	$+\Delta\theta_1$
10	$-\Delta\theta_1$
11	$+\Delta V_3$ $-\Delta\theta_3$
12	B
13	$-\Delta V_3$ $+\Delta\theta_3$
14	C
15	$+\Delta V_1$ $-\Delta\theta_1$
16	D
17	$-\Delta V_1$ $+\Delta\theta_1$
18	E
19	$+\Delta h$
20	F

Table 4. Tape Recorder Format (Continued)

Tape Recorder Channel	Information Bit
21	$-\Delta h$
22	G
23	I
24	H

NOTE: As indicated, channels 3, 8, 11, 13, 15, and 17 contain both incremental velocity and angular rotation information. This is due to the use of gyroscopic accelerometers that sense rotation as well as acceleration. The two quantities are separated by subtracting corresponding gyro and accelerometer outputs during the computation process.

connection directly to the 36-bit data register in the data channel. Since the data word is only 24 bits long, 12-bit positions in the data register were not used.

In the early stages of writing the computer program for processing the data, it became apparent that the computer would have considerable difficulty processing data as rapidly as it was read from the tape. (Although the tape recorder has the ability to play back at a slower speed than the one at which it was recorded, there exists a minimum speed at which satisfactory reading can be achieved.) Morever, since the flight data was recorded as an uninterrupted string of data words, it was not possible to stop the tape recorder periodically to permit the computation to "catch up." Consequently, the program was separated into two phases. The first phase of the processing program would simply read data words from the flight test tape, condense the data format (eliminating the 12 unused bits), and record the data in the new format in 4800 word blocks on standard 1/2 inch magnetic tape. Sufficient time existed for performing this operation without stopping the flight test tape. The standard format tapes would then serve as an input to the second phase of the program. Since they were written in 4800 word blocks, it was possible to halt the tape after reading each block until the computer had finished processing the previous block of data.

The second phase program would then do most of the processing of the flight data. This program evolved into a very elaborate routine with several processing options available to the operator. Only the essential features of the program are discussed below.

The major portion of the second phase program utilized fixed point binary arithmetic, and was written in machine language using the FAP assembly routine. Certain less critical routines (e.g., output routines) utilized floating point Fortran subroutines.

Due to the sensitivity of the system to errors in the incremental gyro outputs, the recorded tape information included 8 parity bits that permitted double error correction on the 6 gyro output bits. The parity check on the gyro bits was the first operation performed by the second phase program. Since this operation had to be performed on each input word, it was necessary to complete it as rapidly as possible so as to avoid using an exorbitant amount of computer time. Consequently, table lookup techniques were used to speed up this portion of the computation (at the cost of using additional memory). Next, the program updated the value of the "B" matrix whenever a nonzero array of gyro bits was encountered. The matrix of direction cosines was then used to transform the velocity pulse outputs from the accelerometers (in the body frame) into velocity increments relative to the inertial frame. These increments were accumulated until the next time inertial position was updated by incremental integration of the differential equation for a pure inertial navigator. This integration was performed every 10-word times. Finally, at fixed intervals, the latest Cartesian coordinates of inertial position were converted to latitude and longitude, and supplied as outputs from the program. A sample computer output is shown in Figure 25. Other outputs from the second phase program included the altimeter reading, velocity in the horizontal plane, parity failure information, the "B" matrix, and the product of "B" and B transpose, all as functions of the time of flight in hours.

Processing of each flight tape was accomplished subsequent to each flight and prior to the next flight. To insure that all of the tape reading and IBM interconnection equipment were functioning properly before processing each flight test, a special test routine was devised. A short section of the beginning of each flight tape was recorded with every word containing all "ones." This section was run through the computer with a program that printed, "on line," each succeeding word and the number of times it occurred. A

I	LATITUDE	LONGITUDE	[illegible]	N-M	INDICATOR
0.	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0	

(THE FOLLOWING MATRICES ARE PRINTED IN OCTAL)

	000000000000	523507544705	140711351772
B =	200000000000	000000000000	000000000000
	000000000000	140711351772	123507544705

	077777777651	000000000000	000000000000
BB(T) =	000000000000	100000000000	000000000000
	000000000000	000000000000	077777777651

0.10	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.20	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.30	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.40	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.50	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
0.60	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.70	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
0.80	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.0
0.90	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
1.00	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
1.10	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
1.20	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
1.30	40 DEGR. 48.08 MIN.	73 DEGR. 6.55 MIN.	0.	0.1
1.40	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
1.50	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
1.60	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
1.70	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
1.80	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
1.90	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.00	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.10	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.20	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.30	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.40	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.50	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.1
2.60	40 DEGR. 48.08 MIN.	73 DEGR. 6.56 MIN.	0.	0.2
2.70	40 DEGR. 48.08 MIN.	73 DEGR. 6.57 MIN.	0.	0.2
2.80	40 DEGR. 48.08 MIN.	73 DEGR. 6.57 MIN.	0.	0.2
2.90	40 DEGR. 48.08 MIN.	73 DEGR. 6.57 MIN.	0.	0.2
3.00	40 DEGR. 48.08 MIN.	73 DEGR. 6.57 MIN.		0.2
3.10	40 DEGR. 48.08 MIN.	73 DEGR. 6.57 MIN.		0.2

FIGURE 25. IBM 7090 COMPUTER OUTPUT (SHEET 1 OF 2)

3.20	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.30	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.		0.2
3.40	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.50	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.60	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.70	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.80	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
3.90	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
4.00	40 DEGR.	48.08 MIN.	73 DEGR.	6.57 MIN.	0.	0.2
4.10	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.20	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.2
4.30	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.40	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.50	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.60	40 DEGR.	48.08 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.70	40 DEGR.	48.09 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.80	40 DEGR.	48.09 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
4.90	40 DEGR.	48.09 MIN.	73 DEGR.	6.58 MIN.	0.	0.3
5.00	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.10	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.20	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.30	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.40	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.4
5.50	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.4
5.60	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.70	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
5.80	40 DEGR	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.2
5.90	40 DEGR.	48.09 MIN.	73 DEGR.	6.59 MIN.	0.	0.3
6.00	40 DEGR.	48.09 MIN.	73 DEGR.	6.60 MIN.	0.	0.4
6.10	40 DEGR.	48.09 MIN.	73 DEGR.	6.60 MIN.	0.	0.4
6.20	40 DEGR.	48.09 MIN.	73 DEGR.	6.60 MIN.	0.	0.5
6.30	40 DEGR.	48.09 MIN.	73 DEGR.	6.60 MIN.	0.	0.5
6.40	40 DEGR.	48.09 MIN.	73 DEGR.	6.61 MIN.	0.	0.5
6.50	40 DEGR.	48.09 MIN.	73 DEGR.	6.61 MIN.	0.	0.7
6.60	40 DEGR.	48.09 MIN.	73 DEGR.	6.61 MIN.	0.	0.8
6.70	40 DEGR.	48.09 MIN.	73 DEGR.	6.61 MIN.	0.	0.9
6.80	40 DEGR.	48.08 MIN.	73 DEGR.	6.62 MIN.	0.	1.0
6.90	40 DEGR.	48.08 MIN.	73 DEGR.	6.62 MIN.	0.	1.0

PARITY FAILURE INFORMATION

776000000000	576000000000	576000000000
576000000000	576000000000	576000000000
576000000000	576000000000	776000000000
776000000000	576000400000	576000000000
576000400000	576000000000	576000000000
576000000000	576000000000	776000000000

7.00	40 DEGR.	48.08 MIN.	73 DEGR.	6.62 MIN.	0.	1.1
7.10	40 DEGR.	48.08 MIN.	73 DEGR.	6.62 MIN.	0.	1.1
7.20	40 DEGR.	48.07 MIN.	73 DEGR.	6.63 MIN.	0.	1.1
7.30	40 DEGR.	48.07 MIN.	73 DEGR.	6.63 MIN.	0.	1.1
7.40	40 DEGR.	48.07 MIN.	73 DEGR.	6.63 MIN.	0.	1.2
7.50	40 DEGR.	48.06 MIN.	73 DEGR.	6.64 MIN.	0.	1.3
7.60	40 DEGR.	48.06 MIN.	73 DEGR.	6.64 MIN.	0.	1.4
7.70	40 DEGR.	48.06 MIN.	73 DEGR.	6.65 MIN.	0.	1.6
7.80	40 DEGR.	48.05 MIN.	73 DEGR.	6.65 MIN.	0.	1.8
7.90	40 DEGR.	48.05 MIN.	73 DEGR.	6.66 MIN.	0.	2.0
8.00	40 DEGR.	48.04 MIN.	73 DEGR.	6.66 MIN.		2.3
8.10	40 DEGR.	48.04 MIN.	73 DEGR.	6.67 MIN.		2.5

FIGURE 25. IBM 7090 COMPUTER OUTPUT (SHEET 2 OF 2)

malfunction in any channel would be indicated by the complete dropout, or a high percentage dropout in the bit associated with that channel; immediate steps could be taken to make necessary adjustments.

The advantages of recording sensor information during flight became apparent when it became necessary to reprocess certain tapes. On several occasions, flight tapes were reprocessed with minor changes in the program either (1) to provide more detailed information on the mode of failure for bad flights, (2) to obtain satisfactory test results despite a failure in the altimeter, or (3) to detect errors in the computation due to noise on the computer input lines.

APPENDIX

OPERATION OF THE RATE INTEGRAL GYRO

The rate integral gyro is basically a single-degree-of-freedom gyro with a supporting structure allowing precessions about the gyro's output axis. The operation of the rate integral gyro is described with the aid of the diagram shown in Figure 26. If the bearings shown along axis A-A were truly frictionless, then any rotation of the vehicle about axis A-A would result in a relative motion between the readout device attached to the gyro head and the instrument case, which is rigidly attached to the airframe.

Due to bearing friction about the axis of rotation A-A, however, a torque is transmitted to the gyro element whenever rotation of the airframe about this axis occurs. This friction torque, if uncompensated, would cause the gyro element to precess about the flotation axis B-B. Such rotation would be intolerable. This precession is prevented by the following sequence of events: the pickoff senses the precession and supplies a signal to the torque motor, resulting in a countertorque just sufficient to balance the friction torque about axis A-A. Precession about axis B-B is thus prevented.

The behavior of this sensor in the presence of rates about other axes can be described as follows. Angular inputs about flotation axis B-B result in the motion of the outer cylinder relative to the inner cylinder (gyro element). This relative motion produces a signal from the pickoff. The pickoff signal energizes the torque motor producing a torque about axis A-A. This torque causes a precession rate about axis B-B just sufficient to allow the inner cylinder to follow the outer one.

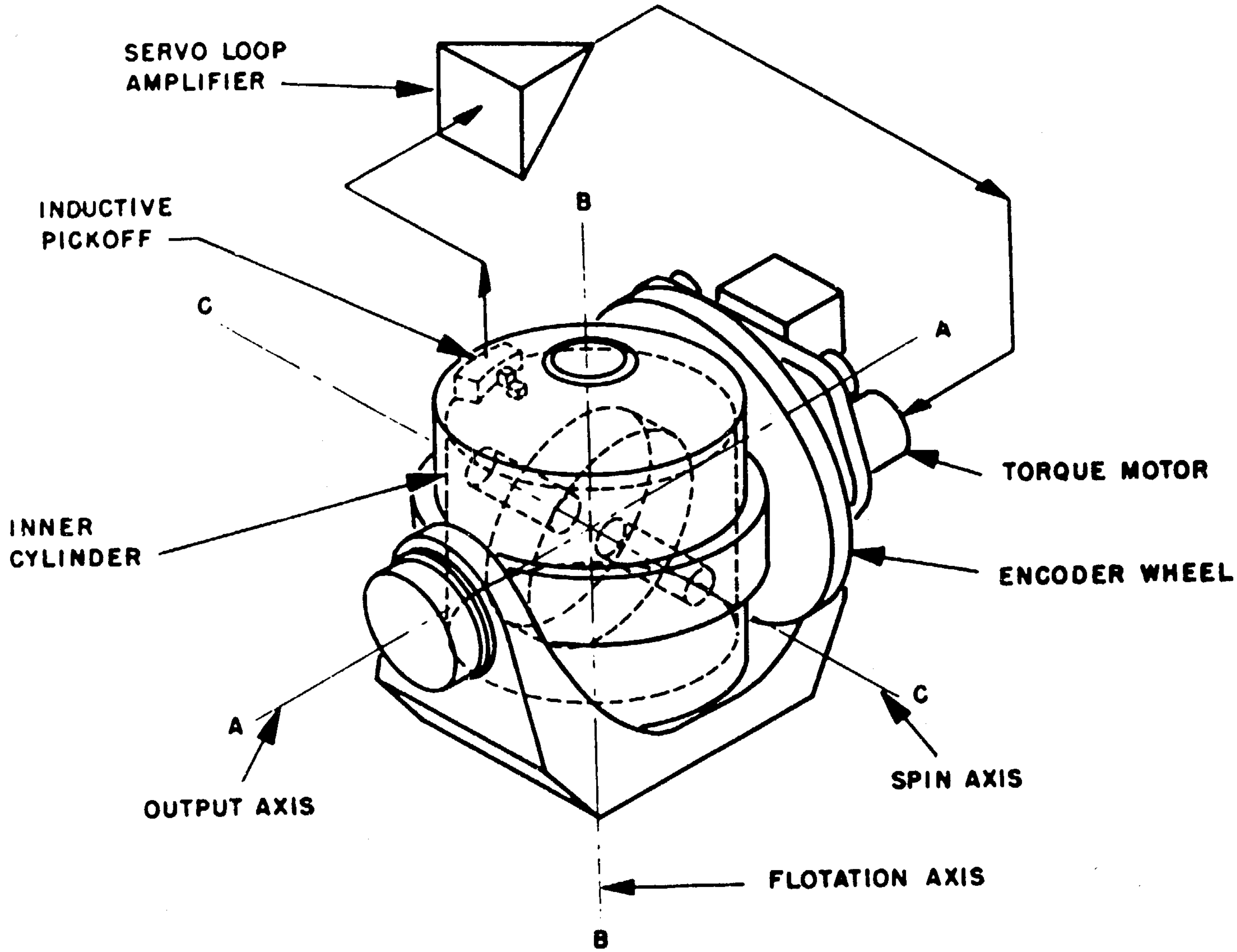


FIGURE 26. RATE INTEGRAL GYRO CONFIGURATION

Angular rates about the spin axis C-C effectively alter the angular momentum of the gyro. The magnitude of torque required for maintaining the pickoff at the null position therefore differs slightly from the torque required in the absence of rates about the spin axis. Since the rate integral gyro does not operate on the torque balance principle (as does the rate gyro), these torque variations do not appear as errors in the output of the sensor.

A readout device (incremental encoder) is coupled to the rate integral gyro output shaft and serves to convert the output to a form compatible with the digital computer. The angular velocity of the digital code wheel represents the vehicle's angular rate about a particular body axis.